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# Decision making under deep uncertainties: A review of the applicability of methods in practice

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ABSTRACT

Deep uncertainties like environmental and socio-economic changes create challenges to decision making. Decision Making under Deep Uncertainty (DMDU) methods are recognised approaches to navigate deep uncertainties and support robust and adaptable decisions. However, their ability to fully reflect the context in which these decisions are made has been criticised. This paper presents a synthesis across cases and methods to provide a holistic understanding of the application of DMDU methods to support long-term decision making. We carried out a structured literature review and analysed 37 infrastructure DMDU case studies. The analysis shows that DMDU methods are effective at developing plans to address a range of deep uncertainties and in some cases, reflecting the institutional context of the decision. However, they largely overlook the organisational and individual contexts in which decision making happens. We argue that the use of existing DMDU methods in practice should start with a better understanding of the institutional, organisational and individual contexts. We then suggest modifications to the applications of DMDU methods, i.e. internalising the context at different stages of the decision-making process and developing a decision typology to signpost decision makers to the best approach for a specific context.

*Abbreviations*
DMDU: Decision Making under Deep Uncertainties

## 1. Introduction

Society is facing unprecedented environmental and socio-economic changes such as climate change, automation, and urbanisation, and many of the uncertainties associated with these changes cannot be quantified or eliminated (Leach et al., 2010; Walker et al., 2013). These types of uncertainty are described as deep uncertainty where it is difficult to agree on the relationships between the key driving forces of change in the long-term or on the probability distributions used to represent uncertainty about those factors (Lempert et al., 2003). These deep uncertainties can involve all aspects of a long-term strategic planning problem—external developments, the appropriate (future) system, and the valuation of system outcomes by (future) stakeholders. It is difficult to make decisions in the presence of deep uncertainty because the effect of decisions cannot reasonably be predicted, and the desirability of outcomes cannot always be agreed on or valued (Leach et al., 2010; Lempert et al., 2003).

Infrastructure systems[1] are particularly prone to this dilemma and we use them as a case to illustrate the challenges of decision making under deep uncertainty. It is widely acknowledged that infrastructure systems must be transformed to avoid precipitating environmental breakdown (Hall et al., 2012; National Infrastructure Commission, 2018). Furthermore, infrastructure is vulnerable to the effects of environmental and socio-economic changes (such as global heating and demographic change) and must adapt to changes already set in motion. However, infrastructure assets are generally long-lived, highly interconnected and subject to governance from a range of public and private organisations. In such a complex system, defining cause and effect is impossible and outcomes emerge from the behaviour and interaction of intermediate assets and actors (Butler, 2008; Hallegatte et al., 2012; Wynne, 1992). Transforming this complex system involves high stakes, in terms of the investment required and the societal implications of change (or lack of change) (Wynne, 1992).

Infrastructure research has progressed significantly, identifying

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[1] By which we mean the networks of energy, transport, water, waste and digital assets and supporting systems of governance and operation that support economic and social development.

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options for transformation in the face of these deep and interacting uncertainties. However, action to transform infrastructure is slow and decision-making processes remain reactive (Davies et al., 2018). The complexity of infrastructure systems, in combination with the long lifetimes and high stakes of infrastructure projects, mean that reactive decision making is insufficient and is unlikely to result in assets that are resilient to future change. Therefore, decisions need to appropriately represent future conditions or plan for adaptation to changing conditions (Marsden and McDonald 2019).

Anticipating future conditions is increasingly difficult and research developing modelling and decision support approaches to inform decisions under deep uncertainty is increasing as a result (Marchau et al., 2019). These approaches and tools supporting the design of policy and plans under conditions of deep uncertainty are collectively termed Decision Making under Deep Uncertainty (DMDU) methods. DMDU methods are based on a "monitor and adapt" paradigm, which aims to prepare for uncertain events and adapt, rather than a "predict and act" paradigm, which aims to predict the future and act on that prediction (Walker et al., 2013). This "monitor and adapt" paradigm "explicitly recognizes the deep uncertainty surrounding decisionmaking for uncertain events and long-term developments and emphasizes the need to take this deep uncertainty into account" (Marchau et al., 2019, p. 11).

Many case studies discuss the application of DMDU methods. These individual examples are very useful to understand how DMDU methods have been applied in specific circumstances. This paper aims to build on existing work to draw generalisable lessons from application of specific methods (Jeuken et al., 2015; Malekpour and Newig, 2020). It presents a synthesis across cases and methods to provide a more holistic understanding of the application of DMDU methods in long-term decision making.

## 2. Supporting decision making under deep uncertainties in infrastructure

### 2.1. Traditional decision making

The rationality paradigm (akin to the "predict and act" paradigm noted in Section 1) has dominated long-term infrastructure planning (Alexander, 1984). Under this paradigm 1) potential states of the futures can be predicted with a reasonable degree of confidence, 2) weights or probabilities can be used to assess likelihoods even if multiple potential futures states might exist, 3) the emphasis is on gathering more information to improve the accuracy of predictions and future actions, and 4) agreement exists both on assumptions about current or future conditions (often on the basis of historical information), and about options' performance against objectives and future predicted states (Decker, 2018; Walker et al., 2013). Yet deep uncertainties and complexities force policy makers to re-think these assumptions.

Determinants of deep uncertainty for infrastructure are multi-faceted and include the impacts of climate change on infrastructure resilience and investment needs (Buurman and Babovic, 2016), developments in information and communications technology (ICT) that in turn influence behaviours and infrastructure needs (Lyons et al., 2018) and more traditional factors of population growth, utility price, disposable income and land-use distribution (Lyons and Marsden, 2019). These deep uncertainties mean that traditional decision support approaches based on probabilistic analysis of future conditions are inappropriate, calling into question the reliability and effectiveness of actions developed using such approaches.

### 2.2. DMDU methods

A growing academic and policy literature considers the merits of DMDU approaches (Marchau et al., 2019). Such approaches invert the analytical steps of a traditional decision-making approach to determine those decision strategies that are robust to a wide range of possible futures or which allows adaptation to changing conditions (Walker et al., 2013). In this paper we follow Marchau et al. (2019) and focus on Robust Decision Making (RDM), Dynamic Adaptive Planning (DAP), Dynamic Adaptive Policy Pathways (DAPP), Info-Gap Theory (IG) and Engineering Options Analysis (EOA). Short descriptions of these DMDU methods follow.

Robust Decision Making (RDM) uses multiple views of the future to identify a plan that performs well in a range of possible futures, avoids situations where it might fail and identifies conditions under which its goals would not be achieved (Lempert et al., 2010). Performance of options can be assessed in a range of different ways but McPhail et al. (2018) suggest it should include the value the decision maker is seeking to achieve (e.g. absolute performance or satisfaction of constraints), the level of risk aversion (determining how many of the subset of scenarios are used for comparison) and the overall objective (e.g. maximising average performance, minimising variance etc.). RDM incorporates adaptability to the extent that it helps to identify hedging actions to address vulnerabilities (Hall and Murphy, 2012; Lempert and Groves, 2010).

Dynamic Adaptive Planning (DAP) makes adaptation of a plan explicit from the outset by developing a 'basic' plan along with monitoring (to determine whether the plan is on-course) and corrective actions (to implement if the plan is not on-course) (Kwakkel et al., 2010; Walker et al., 2001). Planners specify objectives for future development, determine how these objectives will be met through a series of activities, identify vulnerabilities of those activities and identify contingency actions (Walker et al., 2019). Contingency actions include mitigating actions (to reduce adverse effects of a plan), hedging actions (to spread or reduce the uncertain adverse effects of a plan), seizing actions (to seize available opportunities) and shaping actions (to reduce failure or enhance success) (Walker et al., 2013). Signposts or triggers are identified which signal when further reactive action is required (Van der Pas et al., 2013). At the core of DAP are adaptability and directing activity towards a goal through monitoring and contingency actions. DAP relies on predicting potential vulnerabilities and forces planners to make decisions to change and adapt plans continuously (Walker et al., 2019).

Dynamic Adaptive Policy Pathways (DAPP) integrates two partially overlapping and complementary approaches; DAP and Adaptation Pathways (AP) (Haasnoot et al., 2013). AP provide an analytical approach for exploring and sequencing a set of possible actions based on alternative external development over time. The AP approach is based on the notion of adaptation tipping points, where it is assumed that all actions might fail when operating conditions change (Kwadijk et al., 2010). DAPP places greater emphasis than DAP on system analysis to identify objectives, constraints and uncertainties that will inform decision making (Haasnoot et al., 2013). Scenarios are created to identify challenges and opportunities, and actions required to mitigate challenges or exploit opportunities. These actions are classified in the same way as DAP as shaping, mitigating, hedging and seizing actions. Contingency actions and triggers are specified to pre-empt a response when an action meets a tipping point and to enable pathways to be kept open as long as possible, reducing the number of terminal pathways. The results are presented in a graphic format which identifies pathways, tipping points, and any alternative routes after a tipping point (which includes transfers onto different pathways). This allows planners to identify opportunities, no regret actions (such as pathways which have several options once a tipping point is reached), lock-ins (pathways which have no options once a tipping point is reached) and the timing of important actions. A final step is to identify a set of preferred pathways and to plan contingencies to improve the robustness of these pathways. This can include identification of institutional and socio-cultural conditions that can enable preferred pathways (Van der Brugge and Roosjen, 2015). The DAPP approach includes monitoring to continually assess the implementation of the plan and to apply contingency actions where necessary. Furthermore, it includes monitoring of the situation, objectives and uncertainties to assess whether more fundamental

changes to the plan are required, making it a more dynamic process.

Info-Gap Theory (IG) identifies management options that perform acceptably well under a wide range of conditions; seeking robustness rather than optimality in a process known as robust-satisficing (Ben-Haim, 2010). A strategy of satisficing robustness can be described as one that will satisfy the minimum performance requirements (performing adequately rather than optimally) over a wide range of potential scenarios even under future conditions that deviate from the best estimate (Ben-Haim, 2001). Info-gap begins by constructing a representation of the uncertainty, which it then uses to estimate the consequences of alternative decisions provided exogenously to the analysis. The approach informs decision makers by providing them with trade-off curves that compare these strategies according to two criteria it calls "robustness" and "opportuneness." (Hall et al., 2012). The "robustness" of an alternative is the greatest horizon of uncertainty up to which that alternative satisfices critical outcome requirements and "opportuneness" of a decision alternative is the lowest horizon of uncertainty at which that decision enables better-than anticipated outcomes (Ben-Haim, 2019).

Engineering Options Analysis (EOA) is the "process of assessing the value of including flexibility in the design and management of technical systems" (de Neufville et al., 2019, p. 117). EOA calculates the value of options (e.g. the benefits due to flexibility in the timing, size and location of changes in the engineering system) in terms of the distribution of additional benefits due to the options and EOA presents these benefits to decision makers according to different criteria like average expectations, extreme possibilities and initial capital expenses (Capex) (de Neufville et al., 2019).

### 2.3. DMDU application context

These approaches offer real advantages in enabling (virtual) experimentation and building robustness or flexibility, which are crucial to accommodate deep uncertainty. Detailed reviews of the application of some methods exist (e.g. adaptive planning (Jeuken et al., 2015; Malekpour and Newig, 2020)) but research generalisable across DMDU approaches addressing how they might offer decision support in a specific context is still scarce (Kwakkel and Haasnoot, 2019). Caballero and Lunday (2020) highlight the lack of understanding of the structure/-framework in which the decision is made (which we call the context) as a barrier to actual decision making. The broader context of the decision will have, in many cases, a significant influence on the options identified to resolve this decision and their benefits (Ranger et al., 2013). If this context is ignored, decision makers can find it difficult to use tools and/or the solutions developed using such tools can be difficult to implement or ineffective (Roelich and Giesekam, 2019).

We argue that the context of a decision is multi-layered: decision makers are part of organisations that in turn are embedded in institutions and these three levels of context influence and shape each other. Our understanding of the relations between these levels (Fig. 1) is very similar to Cuppen et al. (2020) although out definition of each level differs. Importantly, Cuppen et al. (2020) note that individuals engage with both the organisational and institutional levels simultaneously.

The institutional context (historical, sociocultural, economic and political factors) shapes the feasibility of options available to decision makers and the likely flexibility of a decision. For example, institutional conditions, such as legislation and responsibilities, or socio-cultural conditions, like belief systems, economic activities or state of knowledge on an issue, enable certain options whilst hampering others (Van der Brugge and Roosjen, 2015). Similarly, factors such as political aversion to making mistakes can constrain experimentation and limit flexibility.

Organisational aspects are paramount in shaping the willingness and ultimate success of applying DMDU approaches (Bloemen et al., 2019). If an approach is not well-aligned with accepted organisational processes, practices and resources, it is unlikely to be adopted. Or if the solution proposed is at odds with the objectives of an organisation involved in its delivery, it is unlikely to be effective (Roelich and Giesekam, 2019). In turn the norms, values and processes of organisations can be shaped by the institutional context (Suddaby et al., 2010). Institutional settings are responsible for reinforcing and perpetuating organisational characteristics and for maintaining patterns of continuity that could support or hinder organisational activities (Buchanan and Fitzgerald, 2011).

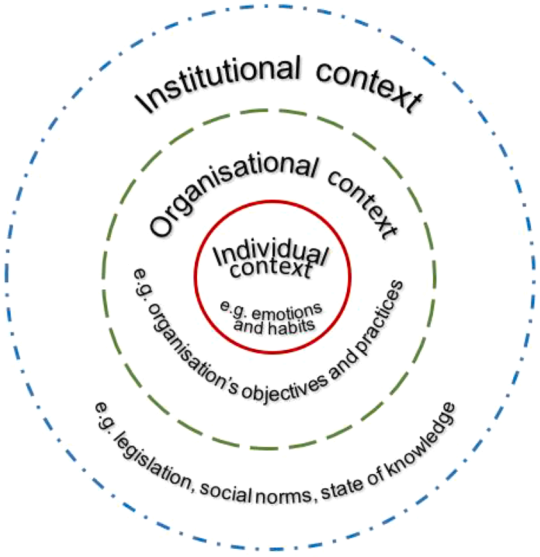


**Fig. 1.** Relations between institutional, organisational and individual context adapted from Cuppen et al., 2020.

Decisions are made based on incomplete information and a limited ability, and often time, to process information (Lindblom, 1959). The notion of 'comprehensive rationality' has long been rejected by psychology and cognitive science. Decision makers navigate their 'bounded rationality' by prioritising certain kinds and sources of information and by drawing on emotions, beliefs, habits and what is familiar to them (Cairney and Weible, 2017). Their experiences and values can have considerable influence over how they use decision support tools and interpret and implement their outputs. Additionally, organisational culture and institutional dimensions guide, to a considerable extent, the actions and interactions of the actors involved in the decision (Termeer et al., 2012) and influence the way decision makers perceive and interpret information and implement decisions.

There is increasing attention to the selection of appropriate DMDU methods. Kwakkel and Haasnoot (2019) propose that different situations warrant different combinations of DMDU methods; "(…) rather than arguing over whether to apply RDM or DAPP, the discussion should be which combination of tools are appropriate to use given the nature of the problem situation (p.370)". This highlights the importance of matching methods to the *nature of the problem situation*, but it is not clear to what extent the problem situation incorporates the institutional, organisational and individual context. Existing literature has identified a need to treat the institutional (e.g. in van der Brugge and Roosjen (2015), organisational (e.g. in Bloemen et al. (2019)) and individual (e.g. in van Dorsser et al. (2018)) factors with greater consideration than has been done when applying DMDU methods. Therefore, this paper examines the extent to which existing DMDU case studies took these three context levels into consideration.

## 3. Methods and data

### 3.1. Method

The previous section emphasised the importance of context on the

effectiveness of a decision support method under deep uncertainties. Yet, previous literature suggested that institutional, organisational and individual contexts have often been overlooked in existing studies (Volkery and Ribeiro, 2009). In this paper, a structured literature review was carried out to collate case studies using DMDU methods for supporting decisions in infrastructure sectors.

The documents included in this study were selected using a structured and systematic search approach in Google Scholar. The review was carried out in three steps: 1) searching for documents in Google Scholar using different keyword combinations; 2) screening of the returned documents; 3) collation and analysis of the results from the subset of included documents (Fig. 2). Google Scholar was chosen over Web of Science or Scopus because it searches across articles, theses, books, abstracts and other academic texts returning primarily peer-reviewed documents but also non-peer-reviewed documents like projects reports, conference and working papers (Younger, 2010). This was important for this topic because many case studies applying DMDU methods are conducted by non-academic institutions and could have been missed by searching only academic publications.

When selecting the search terms, care was taken to use the same combination of keywords. i.e. "deep uncertainties" AND [DMDU method] AND [infrastructure sector] and "case study", where [DMDU method] is successively Robust Decision Making, Dynamic Adaptive Planning, Dynamic Adaptive Policy Pathways, Info-Gap Decision Theory and Engineering Options Analysis and [infrastructure sector] is successively water, power and energy, transport, telecommunications and waste. The twenty-six searches yielded a total of 2053 documents (including duplicates). The documents were screened using four inclusion criteria and only the documents complying with all of these criteria were retained. These four criteria specified that documents must be 1) written in English (both abstract and full text), 2) applying the following DMDU methods: Robust Decision Making, Dynamic Adaptive Planning, Dynamic Adaptive Policy Pathways, Info-Gap Decision Theory and Engineering Options Analysis, 3) covering the infrastructure sectors water, power and energy, transport, telecommunications and waste, and 4) published between 2010 and the end of February 2020, when the search in Google Scholar concluded.

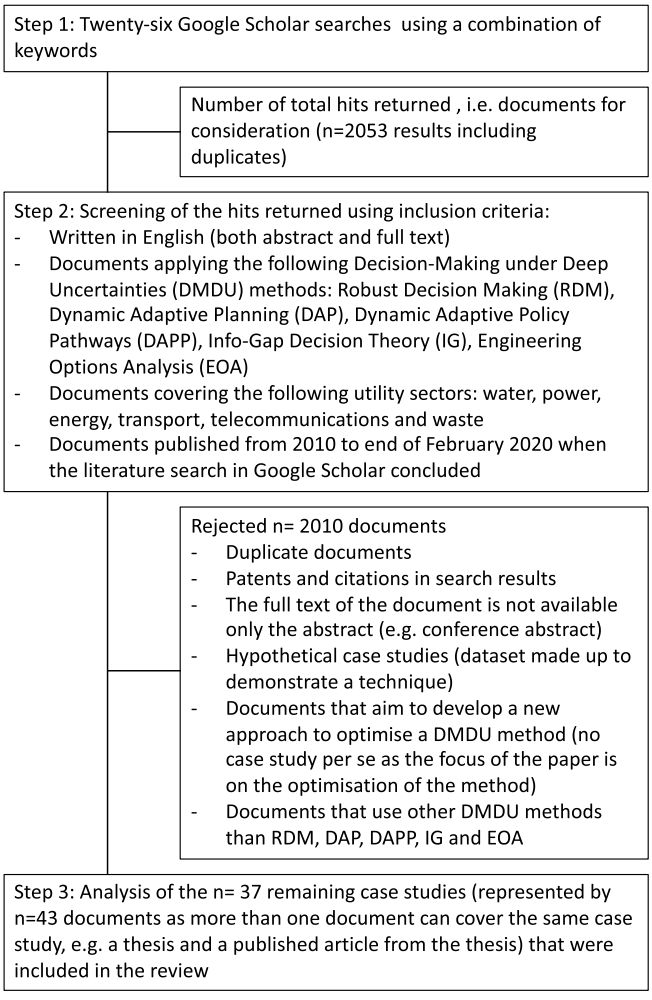


**Fig. 2.** The 3-step process followed to carry out the review.

A first broad search with a combination of terms "deep uncertainties" AND "case study" AND "decision making" was first carried out and returned 932 hits of which 88.5% covered the period 2010-February 2020 and 11.5% the period pre-2010. After close examination, although literature emerged pre-2010 on DMDUs, papers mainly focussed on describing the approaches and no "real" case study applications using the DMDU methods could be found in the 108 hits returned before 2010; this review therefore used only literature published in the last decade.

Data analysis determined the extent to which the case studies included took institutional, organisational and individual contexts into consideration. These three levels were included as Section 2 has previously highlighted the importance of these three context levels for decision-making under deep uncertainty. Following screening, 43 documents were retained and imported into MaxQDA, a qualitative data analysis software. They were then coded by the broad setting of the case study and by the three core themes of institutional, organisation and individual contexts. Within each of the three core themes, additional sub-themes were identified deductively so the final list of themes included: nature of the decision, institutional context (including system complexity and sources of deep uncertainty/ies, stakeholder(s) involved), organisation context (nature of the organisation, organisation processes) and on the decision maker.

### 3.2. Data

Forty-three documents covering 37 case studies were analysed in this study. More documents than case studies are presented as two documents could cover the same case study; for example, a case study could be outlined in a PhD thesis and a corresponding peer-reviewed article derived from that thesis. Some documents cover the same geographical area and have the same over-arching sector (e.g. water) but their focus might differ (e.g. water management, governance, etc.). In this case, these documents were treated as separate case studies. The unit of analysis is the case study (and not the document) as the focus of this study is to gather as much information about a decision (within a case study) as possible, even if it is derived from different sources. The number of documents outlining DMDU case studies rose steadily from 2010.

Out of these 43 documents, 19 are peer-reviewed and 24 are not (e.g. thesis, reports, book chapters, working papers, conference papers). The geographical coverage of the 37 case studies is: Europe: 11 (30%); North America: 9 (24%); Asia: 9 (24%); Australia/New Zealand: 3 (8%) Africa: 3 (8%); South America: 2 (5%). The infrastructure sectors the case studies cover are predominantly water (inc. coastal, urban flooding, water supply, sea level rise etc.): 28 (76%), then transport: 6 (16%), power and energy: 2 (5%) and one study covers several utility sectors (3%). The case studies use mostly RDM (Inc. Many-Objective RDM); 19 (53%). Results from the search on DAPP revealed more studies covering Adaptation Pathways (AP; 10 (26%)) than DAPP studies per se (DAPP; 5 (13%)). Fewer studies used DAP (2 (5%)) and IG: 1 (3%) and none covered EOA: 0 (Fig. 3). One the study covers both RDM and IG, comparing the outcome of both methods for the same case study (Matrosov, 2015).

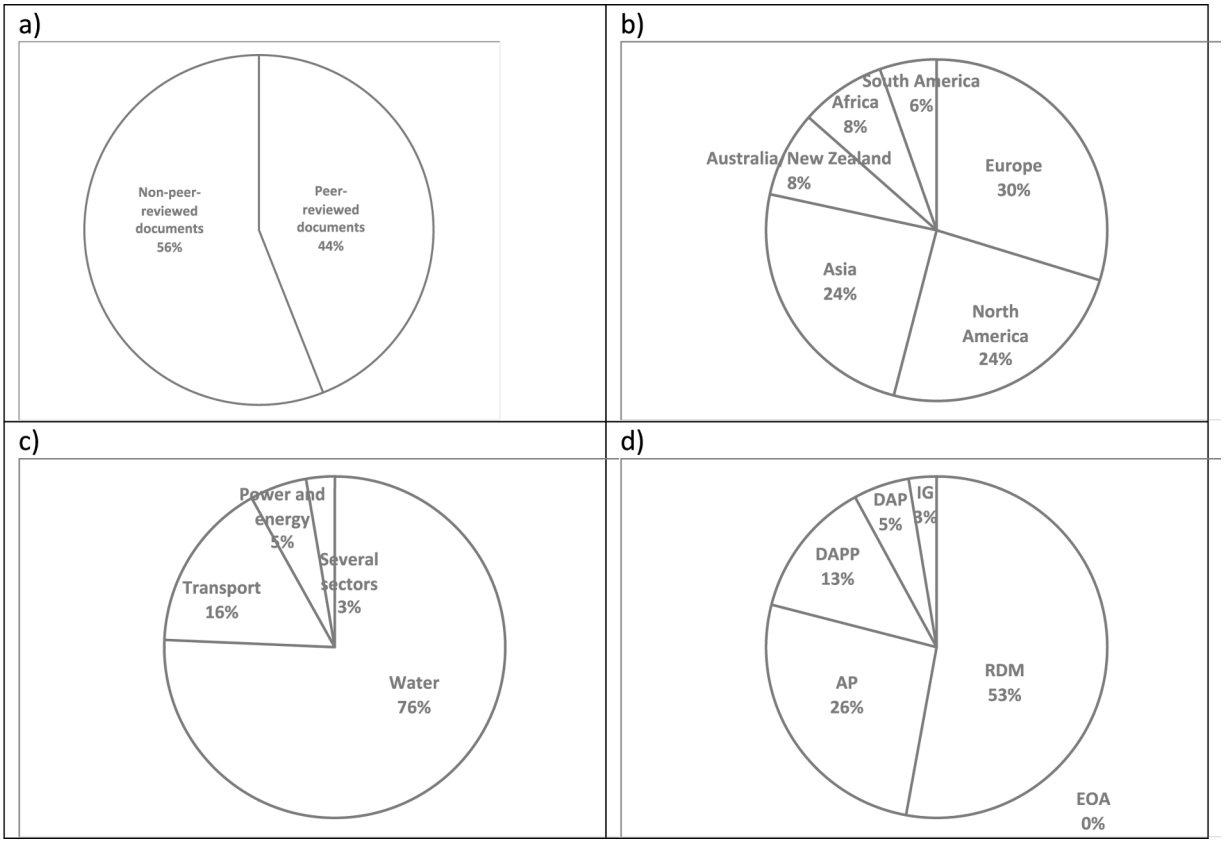


**Fig. 3.** Characteristics of the case studies included (a) Peer- or non-peer-reviewed documents; b) Geographical coverage; c) Infrastructure sector(s) covered and d) DMDU used).

### *3.3. Limitations*

Excluding non-English language documents may introduce bias into our work. Application of DMDU methods is particularly prevalent in the Netherlands and this work might have been reported in Dutch. We recognise this as a limitation of our work, which aims to be systematic and identify generalisable lessons, but is not exhaustive.

Using documents as our source of data presents several limitations too; in many cases it is not clear what was the relationship between the document and the actual decision being made (i.e. at what stage of a particular decision making process it was developed and what role it played in making the decision). Furthermore, documents are necessarily limited in what they report, the word limit peer reviewed journals impose on authors often challenge the reporting of their research (Blignault and Ritchie, 2009). The intended (predominantly academic) audience of word-limited publications and using data only from documents might exclude discussions about context that affected analysis in reality. Our results are analysed in light of these limitations.

## 4. Results

About 80% of the case studies included are prospective, i.e. demonstrate how a method could be applied, "experiments" to guide potential decision makers or are exploratory research projects. The considerably smaller number of retrospective case studies, i.e. studies actually having been implemented or developed on behalf of designated decision-makers. We did not trace the prospective studies to detect whether they affected decisions in later stages of the decision making process, but the overall balance between prospective and retrospective studies does support Coals et al. (2019) finding that; over the years, "inquiries focused on methods for DMDU have largely focused on developing technical tools for evaluating robustness and better forms of adaptive planning" (p. 10) rather than implementing DMDU methods in practice. In the next sections, we examine the extent to which the three levels of institutional, organisational and individual contexts were considered during the application of DMDU methods.

### 4.1. Nature of decisions

The first part of the results outlines the inherent characteristics of decisions the case studies considered and explores whether and how approaches addressed these characteristics.

Decisions described in the reviewed documents are predominantly high stake for several reasons. Firstly, because of their potential for lock-in and high sunk costs, which means that decisions are not easily reversible. This could be a direct decision about whether to invest in a new power plant (e.g. Hurford (2016)) or indirectly as part of a water management plan (e.g. Kalra et al. (2015)). Secondly, because of the potentially disastrous consequences if the problem remains unmitigated (lives lost, property damaged and economic disruption) or if the potential for maladaptation is significant. Decisions often concerned the management of resources that are critical for a particular area (e.g. Groves and Bloom (2013)) or an area that is highly exposed to risk (e.g. Groves et al. (2014)), which magnified these disastrous consequences. Finally, decisions can generate conflict over potential solutions (e.g. a hydropower dam with a potential cross-country conflict over water resources; (Jeuland and Whittington, 2014)).

The high stakes of decisions matter for decision making under uncertainty because they make it more difficult to experiment – the costs and consequences of any experiment could be too high, and many decisions are irreversible. Many infrastructure decisions made now will have consequences not only for the near future but also in the longer term. The effects of some infrastructure can even be observed after it has become obsolete (Gusdorf et al., 2008). Furthermore, the highly contested nature of responses, which are visibly political, means that decision makers cannot be seen to be taking 'wrong' decisions. This gives limited degrees of freedom.

The approaches described in the reviewed documents addressed the high stakes and low degrees of freedom by creating virtual experimentation environments, allowing decision makers to assess the consequences of decisions and identify plans that build in flexibility and reduce societal impacts. The approaches frequently acted as 'boundary objects' which facilitate interaction and sense-making and reduce conflict around different understandings of the system or outcomes (Barreteau et al., 2012; Cuppen et al., 2020).

The approaches presented in the reviewed cases adopt a "monitor and adapt" approach rather than a "predict and act" approach that consists of using long-term scenarios (e.g. climate scenarios) to drive the decision. In "monitor and adapt" approaches, the process begins at the level of the decision, specifying its objectives and constraints, contrasting to the "predict and act" approach where scientific outputs drive the decision outcome (Gregory et al., 2012). In "monitor and adapt" approaches, the nature of the decision and its characteristics should guide the choice of the supporting approach chosen to make the decision. Yet, the reviewed papers included in our study rarely justify why the specific "monitor and adapt" approach selected was the best fit to tackle the decision at hand in the case studies (see also Kwakkel and Haasnoot (2019)). This lack of justification further highlights that the decision context might be overlooked in the section of DMDU methods as well as in their application .

### 4.2. Institutional context

In the reviewed documents, two characteristics predominantly define the institutional context a decision takes place in: complexity and multi-stakeholders.

#### 4.2.1. Complexity

The problem situation in the studies analysed is described in terms of a number of different types of uncertainties, which address many elements of the institutional context of the system of interest. These include: changes in environmental conditions (climate change e.g. extreme weather events, flooding, reduced water availability, sea level rise, cyclone frequency) is included in 37 of the 43 reviewed documents (95% of the documents); changes in socio-economic conditions (inc. population growth, demographics, economic growth, infrastructure lifetime; 41%); change in future demand or availability for services (like utility services or other services such as air travel; 33%); land use changes (inc. urban development, coastal land loss, 21%); financial uncertainties (e.g. wholesale price of utility, discount rate, fuel prices; 10%); policy uncertainties (3%); and uncertainty associated with the decision maker's subjectivity (3%).

Almost all cases include future changes in environmental conditions together with other uncertainties like socio-economic conditions. The multiple interacting uncertainties mean that the problem situation is complex: the outcome of intervention into the system is difficult to forecast, feedback loops make it difficult to distinguish cause from effect, significant time and spatial lags exist and relationships are non-linear resulting in thresholds (transition points between alternative states) (Costanza et al., 1993; Liu et al., 2007).

The reviewed cases show how DMDU approaches can address this complexity by using large scenario spaces to account for the many different ways the identified uncertainties could evolve. This allowed authors to identify recurrent vulnerabilities and strategies to hedge or mitigate these vulnerabilities. However, the scenario space was defined by the uncertainties deemed to constitute the problem situation in each case. Social, cultural, financial and political uncertainties were not considered universally across cases, meaning that these elements of the institutional context were frequently overlooked. Furthermore, as a network of assets and actors, infrastructure itself is a complex system (Oughton et al., 2018) and is subject to the same instability and unpredictability as the uncertainties considered in the reviewed documents. This 'internal' complexity and the uncertainty associated with the response of infrastructure itself to intervention, is rarely addressed in the case studies included.

#### 4.2.2. Multi-stakeholders

The institutional aspects of the problem situation can further be characterised by the multiple stakeholders who interact in the decision-making space. In the reviewed cases, stakeholders to the decisions are rarely explicitly named but are more often referred to by their functions (e.g. local farmers or fishermen, social organisations, business community, policy makers, residents, public authorities). The document analysis revealed three levels of stakeholder involvement: 1) mention of stakeholder(s) but no specific description of them or how they were involved in the case study (just that they should be involved, for example); 2) stakeholders were involved in the case study to better understand the case study context and to gather information about the case study through workshops, public consultations, etc.; and 3) the stakeholders were engaged in shaping the case study and some effort was made in some studies to understand where there could be conflict

over the decision. The analysis revealed that the majority of the documents included (28 documents or 65% for levels 1 and 2 combined) use stakeholders' consultations and workshops for gathering information about the context of the decision. About a third of the studies (15 documents in level 3 or 35% of the studies) involved stakeholders in problem formulation, deciding on performance metrics, shaping DMDU scenarios or pathways, or other forms of collaboration between action researchers and practitioners. But none of the studies included any stakeholder analysis that would provide a better understanding of their goals and values about the decision at hand, and their assumptions about the decision outcomes. We note that absence of evidence of stakeholder analysis in the documents we analyse does not mean that it was absent from the processes the documents report on. However, the absence of discussion of stakeholder goals, values and assumptions indicates that these issues are not given priority.

Yet, Schneider et al. (1998) note "uncertainty is not purely of a technical or physical or biological character, but also social, cultural and institutional in nature" (p. 170). The nature of infrastructure's complexity implies that many actors in different sectors and at diverse levels need to act to protect wellbeing and planetary health (Ostrom, 2010) and no single focus of decision making will drive the necessary speed and scale of change. Instead responsibility and associated decisions must be distributed across many actors. These actors all have different motivations, framings and decision-making processes and have differing levels of agency over aspects of the complex system within which they are embedded (Roelich and Giesekam, 2019). But if physical uncertainties have long been recognised as sources of deep uncertainty in decision making, societal perspectives have still received little attention in DMDU literature (Haasnoot et al., 2013).

Therefore, by overlooking some aspects of the institutional context (including elements of complexity and stakeholder perspectives), the nature of the situation is not fully represented.

### 4.3. Organisational context

Information on the organisational context is more limited in the reviewed cases. Some explicitly name the organisation responsible for making the decision and give general information on the organisation itself, like what type of company it is (e.g. utility, government body) or what level they operate at (e.g. local utility company, a country's main water agency). Organisational processes are rarely described but a handful of studies do mention how the organisation has historically treated an issue (e.g. climate change; (Dewulf and Termeer, 2015)), what economic metrics the organisation used to appraise a decision (e.g. cost benefit and cost minimisation targets; (Bonzanigo and Kalra, 2014)) or some of the plans and strategies already in place in the organisation. This lack of details on the organisation could be attributed to the fact that the majority of these studies were developed outside of organisations; researchers explored the application of DMDU methods using organisation data but the study was not embedded in the organisation itself.

The success of DMDU approaches depends on the availability of a sufficiently rich decision space from which robust strategies may be determined (Lempert and Collins, 2007). Several "realistic" options need to be available to actually choose from and this ensemble of options can be referred to as a "decision space". However, the feasibility and acceptability of options can be affected by a wide range of organisational factors, such as organisational objectives and culture, which can reduce the decision space extensively, affecting the application of DMDU methods (Head, 2014; Institute of Medicine, 2013). None of the reviewed cases took these organisational factors into account when describing the nature of the situation. Therefore, their outputs could include options which are not viable within the organisational context and thus might overestimate the effectiveness of plans and strategies (Roelich and Giesekam, 2019).

Our results also show a mismatch between the work involved in applying methods and the reality of decision-making in an organisation. This goes beyond the impact on the decision space described above and raises concerns about whether the steps of the methods align well with existing practices. Few DMDU cases engaged with these processes and some studies recognise the limits of their work when it comes to implementation in an organisation setting; for example Barnett et al. (2014) highlight that "further research to test this [method] and provide more detail of the reality of implementation within existing institutions would be beneficial." (p. 1107). Most organisations in the public and private sector have established systems of governance through which options are identified and decisions appraised. DMDU methods must fit with these processes if outcomes of analysis are to be implemented. Bloemen et al. (2019) emphasised that: "DMDU scholars often implicitly assume that their approaches will be automatically welcomed – that this way of reasoning will be embraced politically and accepted institutionally—suggesting that implementing a DMDU approach is mainly a technical and intellectual challenge. Experience, however, shows that in real-life decision-making, organizational aspects play a major role in determining the willingness and ultimate success in applying approaches for dealing with deep uncertainty in practice." (Bloemen et al., 2019, p. 396). These limitations in addressing the organisational context affect the representation of the nature of the situation, in relation to the role of organisational context in limiting decision options, but also affect the 'fit' of DMDU methods with existing organisational processes and culture.

### 4.4. Individual context

Individual decision maker's characteristics are important influencers of decision-making. Yet, decision-makers themselves are given even less attention than organisations. Some case studies outline some decision-makers' generic traits like attitude towards risks (e.g. risk averse versus embracing risks), preferences or judgments when applying DMDU methods (e.g. regarding how to treat uncertainties; e.g. Jeuland and Whittington (2014)), cognitive myopia, where decision makers inadvertently ignore aspects of the problem, or decision maker biases (e.g. Kasprzyk et al. (2013)). However, none of the case studies elaborated on how these traits affected the analysis undertaken.

The exclusion of the individual context presents several problems for the application of DMDU methods, including cognitive and resource limitations, and preferences and expectations. The cognitive and resource requirements of the majority of DMDU techniques are high, which is why they have been applied predominantly on behalf of decision makers, rather than by decision makers. All individuals have limited cognitive capacity and decision makers are frequently operating with limited time. New information/concepts that must be dealt with as a result of DMDU methods could challenge the capacity of many decision makers.

The way that individuals interpret information is socially constructed, and guided by different frames of perception (Schön and Rein, 1994). A "frame" contains individuals' knowledge, assumptions, interests, values and beliefs (Kolkman et al., 2005; Schön and Rein, 1994). Frames shape an individual's decision position because it is within these frames that the individual judges and synthesise the information into a problem solution (Kolkman et al., 2007). Frame differences between individuals are barriers that undermines adequate problem solutions. Identifying and mapping these various frames are therefore paramount for problem-solving but decision makers' values, choices, assumptions, limitations and difficulties are seldom openly communicated (Jäger, 1998) or fully explored in DMDU approaches.

The effects of individuals' framing on the definition on the nature of the situation is not addressed in current DMDU approaches, which could affect outcomes significantly. Cognitive and resource constraints could also affect the 'fit' of DMDU approaches with individual decision makers.

### 4.5. Summary of analysis

Our analysis highlighted several institutional, organisational and individual factors missing from the consideration of the nature of the situation when applying DMDU approaches in the reviewed cases. Yet, these factors are crucial for supporting decision making under deep uncertainties more effectively. Gorddard et al. (2016) emphasise that decision contexts create and limit the set of practical, permissible decisions and influence the capacity for change and transformation. Furthermore, we identified several factors relating to organisation and individual contexts that would affect the practical application of DMDU approaches by organisations. An understanding of the context of a decision at the three levels of institutional, organisational and individual is therefore crucial to achieve the benefits claimed by DMDU approaches and support decisions in reality.

## 5. Discussion

In this section we reflect on the findings of the structured literature review, identify how the limitations of current approaches could be addressed, and discuss how institutional, organisational and individual context could be better integrated in DMDU methods.

### 5.1. Embedding context in the application of DMDU in practice

Academia and the public and private sectors have become increasingly interested in approaches and tools that can support long-term planning in complex systems. DMDU has emerged as a new family of approaches and tools to deal with deep uncertainties and support the development of robust plans (Walker et al., 2013). This new "monitor and act" paradigm explicitly recognises the deep uncertainties surrounding decision making for long-term developments (Marchau et al., 2019).

There are many benefits to applying DMDU approaches. One of the main advantages is in the selection and sequencing of activities to build resilience while avoiding lock-ins and stranded assets (World Bank, 2018). Another advantage of some DMDU methods is the development of several parallel trajectories and possibilities for switching from one trajectory to another when conditions indicate it is necessary. Switching to parallel trajectories is a clear advantage to build a system's resilience in case some of the trajectories do not perform as anticipated (Bloemen et al., 2018). However, whilst academic literature has made significant progress in developing DMDU methods, our analysis has shown that real challenges exist in applying these methods and that application of DMDU methods in organisations is still limited. Malekpour et al. (2016) echo this observation: "Despite the great potential of the new generation of planning approaches [i.e. DMDU methods] to deal with complexities and uncertainties of today's strategic planning for delivery of public services, there is limited evidence of their uptake in practice." (p. 193). This finding would benefit from closer analysis of the relationship between the methods' outputs and the actual decision being made, to detect less direct influences on decisions.

We have also identified a lack of discussion of context in DMDU application, despite evidence showing that understanding the context of the decision is crucial to shaping the nature of the problem situation and to fitting methods with the organisation and individual. We recognise that this finding might be a result of using project documentation, which is limited in what it can report, and that engaging with the research more fully (e.g. through participant observation (Pot, 2020)) might have identified more discussion of these issues. Nevertheless, the absence of discussion of some crucial issues of context across cases indicates that these issues are not given priority. It is not clear from our results whether the lack of consideration of context stems from the way that methods have been applied, or from the methods themselves, however, further research is needed to internalise the consideration of context.

Several steps could be taken to better embed institutional, organisational and individual context and make DMDU methods more applicable in practice. First, at an institutional level, stakeholders need to be organised so that they can develop a broader understanding of the nature of the problem situation (including key institutional and organisational factors) as well as consensus on the decisions that have to be made to tackle it. Second, the organisational context orientates the choice of DMDU method and bounds the decision space; therefore, it needs to be considered carefully when selecting and applying a decision-making approach. Last, the non-rationality and individual preferences of decision maker need to be recognised if DMDU methods are to be used appropriately in decision making.

### 5.2. Organising stakeholders at the institutional level

DMDU methods should be understood as learning and acting processes, taking place over time (Hallegatte, 2014) and not as a unique decision at one point in time. If traditional decision-making approaches are already deeply entrenched (Malekpour et al., 2016), the implementation of DMDU approaches in real situations requires the adaptation or creation of institutions and organisational practices that will carry out this long-term process.

The cases included in this paper highlighted the importance of stakeholders in defining the institutional context decisions are taken in. Indeed, the involvement of stakeholders and decision makers in defining the problem and selecting a DMDU approach to tackle it, is critical (Bhave et al., 2016); under conditions of deep uncertainty, differences in stakeholder opinions and political opposition to action, can lead to paralysis (Hallegatte, 2014). Stakeholders involvement in the decision-making process, although difficult, has potential to 1) increase the commonality of understanding through access to information (Brugnach and Ingram, 2012), 2) build problem-solving capacity at multiple scales (de Boer et al., 2010) and 3) address insecurities regarding uncertain, complex and divergent factors (Bommert, 2010).

Traditional decision-making processes ask stakeholders to first reduce uncertainties by agreeing on assumptions about current and future conditions, and then analyse decision options. When disagreements arise this traditional "agree-on-assumptions" process lacks transparency, is vulnerable to bias and gridlock, and leads to brittle decisions that perform poorly when futures diverge from projections. To avoid this, agreement could be deferred until the problem has been more clearly defined and the options to tackle it under different assumptions thoroughly analysed. This "agree-on-decisions" process promotes consensus around robust decisions and can help manage deep uncertainties and disagreement over issues and conditions (Kalra et al., 2014). Whilst some decision-making approaches assume that experts will provide the "best" solution to decision makers, "agree-on-decision" methodologies build on more participatory styles and close interactions between stakeholders. As such, they can assist the decision maker to evaluate options, to develop strategies, and to evolve preferences in light of the analysis of uncertainties (Ben-Haim, 2006). Such an approach can ensure that decisions are legitimate and more appropriate in the presence of deep uncertainty (Renn, 2008).

### 5.3. Reflecting the decision space at the organisational level

The organisational context of the decision must be fully understood to select an appropriate DMDU approach and to identify 'realistic' options when applying approaches. Not all DMDU methods are suited to support every decision under deep uncertainty. For example, DMDU methods are not suited for budget-constrained decisions as their process is relatively resource-demanding (Dittrich et al., 2016) and some decision methods might not be effective for organisations that use conflicting methods for communicating decision options and uncertainties. As such, rather than one approach fits all, "a menu of methodologies is required, together with some indications on which strategies are most appropriate in which contexts." (Hallegatte et al., 2012). To this end,

Dittrich et al. (2016) reviewed several DMDU approaches and outlined a simple framework to identify which method may best support climate adaptation planning. However, this study only covers climate change so it would be beneficial to extend this to consider other deep uncertainties (such as future demand for infrastructure services) that can have important bearings for the decision at hand and hence the choice of the method to support it.

In addition to more targeted guidance about which DMDU method is suitable for a specific context, DMDU applications in organisation can be further encouraged through 1) adapting an existing DMDU method (e.g. qualitative rather than quantitative application; local versus national application) 2) simplifying a DMDU method or 3) picking elements from the different DMDU methods to suit different stages of the decision process. Barnett et al. (2014) for example, developed adaptation pathways at local level for Lakes Entrance in Australia, using qualitative data derived from workshops and focus groups. Ranger and Garbett-Shiels (2012) built a framework to aid in accounting for uncertain and changing climate in planning and policymaking, using the concept of robustness, central to any DMDU method but in a way that is less data and resource intensive than applying a DMDU method. Bloemen et al. (2019) developed the "Adaptive Delta Management" approach, where elements of DMDU methods are "cherry-picked" to fit well with the mission and task of the Dutch Delta programme and that would offer both structure (for consistency) and flexibility (for tailoring to theme-specific and region-specific characteristics). These novel approaches are promising avenues to support the application of DMDU in practice, but examples are still scarce.

### 5.4. Recognising the non-rationality and individual preferences of decision maker at individual level

The case studies included in this paper gave little consideration to the decision maker themself and assume that actors make rational choices. This supports previous findings that current approaches have been framed from a research and expert perspective that follows a rational approach to decision-making under uncertainty (Dzebo et al., 2015). Under such rationalist perspective, the focus is on developing robust and adaptable plans, not on how these plans will be implemented (Lawrence and Haasnoot, 2017). This overlooks how, or even whether, decisions get made, which can have significant implications for the success of any plan or policy developed through the process of modelling or decision analysis (Roelich and Giesekam, 2019; Van der Brugge and Roosjen, 2015). There is an extensive literature examining the barriers to evidence use in policy making generally, which has relevance to infrastructure decision making. This literature identifies several flaws in the rationalist view of decision making that would render ineffective approaches built on this assumption (Cairney and Weible, 2017). Research has shown that an actor's decision is highly subjective and may include variables such as personal gain, risk tolerance, relevance to related events and value of a decision to the organisation (McCaughey and Bruning, 2010).

One approach that could contribute to better understand the organisational and individual contexts and therefore better tailor the selection and use of DMDU method for a given decision, decision maker and context is the "use case". Use cases are a well-established tool, widely used in developing IT systems (Cockburn, 2000). A use case is a collection of possible sequences of interactions between the system under development and its users, relating to a desired goal and sets up the context within which the system aims to be used (Downing, 2012). Use cases rest on the information provided by the system users. A use case starts with identifying the actors who are going to use the system, then defining what the users want to do, their goals and how the system could support them in accomplishing a particular task. This process collates information on the context the approach will be used in and on the users themselves. Such an approach could be easily followed when developing, not a system per se, but a flexible decision support approach under deep uncertainties. Use cases are therefore promising avenues to better understand organisational and individual contexts and bring DMDUs into real decision-making.

### 5.5. Towards hybrid dmdu approaches that take more account of the decision context

DMDU approaches have real potential to support robust and adaptive decisions for complex systems, but there are many challenges associated with putting DMDU into practice. This can include operational challenges in implementing elements of DMDU approaches (such as defining tipping points and setting up monitoring regimes (Bloemen et al., 2019; Haasnoot et al., 2018; Popper, 2019)). A broader challenge, which was highlighted by our review, is the lack of alignment with existing governance approaches (see also Lawrence and Haasnoot, 2017; Malekpour et al., 2016).

These limitations come from using the DMDU methods "as they were designed to be applied", following prescriptive steps about how to set the problem context, to frame the problem, to explore the uncertainties, to evaluate candidate decisions for robustness and provide decision recommendations (Tsoukiàs, 2008). But they also come from overlooking the context in which they are applied (see Section 4). One way forward could be to keep the "essence" of the DMDU approaches but modify them to take the context more fully into consideration. At this stage, we can see four ways of adapting DMDU methods, to capture their advantages and work around their limitations, to better embed context and make them more applicable to real cases, beyond academia. The first is to extrapolate DMDU approaches from being mainly quantitative to a more qualitative "lighter" approach, for example using stakeholders' social thresholds and consensus (as opposed to quantitative model outputs for example) as tipping points for adaptation pathways (Barnett et al., 2014). The second is to come up with decision support paths that combine various analytical components, i.e. sequence the decision process with different methodological choices for each step of the process from representation of the problem to the problem framing, the evaluation and implementation of the decisions and the monitoring of the decisions (Moallemi et al., 2020). The third is to elaborate a hybrid decision support approach that "cherry-picks" elements from available methods to build an approach that would fit well with the context of the decision (Bloemen et al., 2019). A fourth way forward could be to combine techniques from DMDU literature with techniques from other areas of literature that support long-term planning under uncertainty, but with a more explicit focus on institutional and governance context, e.g. Malekpour et al. (2020) combine DMDU and Transition Management.[2]

## 6. Conclusions

DMDU methods have greater potential than traditional decision-making methods to support decision-making in infrastructure under deep uncertainties. As such they are worth pursuing and efforts have been made to match DMDU methods to particular projects to improve their application in reality (e.g. Dittrich et al., 2016; Kwakkel and Haasnoot, 2019). However, more progress is needed for the methods to leave the academic realm and to be widely used in reality; there is still limited evidence of the uptake of DMDU planning approaches in practice (Malekpour et al., 2016).

We recognise that our analysis is based on data from published works and does not take into account the relationship between these documents and the decision making process they are designed to support. Context might have been considered during the analytical process, but not reported in the final publication. However, it could be argued that because these issues were not mentioned, they were not a central focus

[2] We thank an anonymous reviewer for drawing this option to our attention.

of analysis. Nevertheless, it would be beneficial to analyse active DMDU processes to examine the consideration of context and the extent to which DMDU approaches influence decision making processes less directly in more detail. We demonstrated in this study that the lack of understanding about the context (i.e. institutional, organisational and individual) of the decision might hinder the selection and effectiveness of DMDU methods by excluding key factors from the description of the nature of the problem situation or by overlooking the fit between methods and organisations or individuals. It is not clear whether this lack of consideration of context is related to how DMDU methods are applied, or the methods themselves. However, the institutional, organisation and individual contexts are not embedded in the analytical methods and tools that constitute DMDU approaches, which means it is not currently clear how these contexts should be internalised (Malekpour et al., 2020). It would be beneficial to provide guidance on embedding context for those applying DMDU.

This guidance should include developing a better understanding the institutional context the decision is embedded in and particularly the various stakeholders involved, and their goals, values and assumptions. The organisational context itself also needs to be given further consideration as it can orientate the decision space, and the choice and application of the DMDU method appropriate to support a specific decision. Finally, the bounded-rationality and individual preferences of decision makers need to be recognised if DMDU methods are to be used beyond academia.

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## CRediT authorship contribution statement

**Muriel C. Bonjean Stanton:** Conceptualization, Methodology, Data curation, Formal analysis, Writing - original draft. **Katy Roelich:** Conceptualization, Writing - original draft, Supervision.

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