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Choosing small sets of policy-relevant scenarios by combining vulnerability and diversity approaches

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ABSTRACT

Computer simulation models can generate large numbers of scenarios, far more than can be effectively utilized in most decision support applications. How can one best select a small number of scenarios to consider? One approach calls for choosing scenarios that illuminate vulnerabilities of proposed policies. Another calls for choosing scenarios that span a diverse range of futures. This paper joins these two approaches for the first time, proposing an optimization-based method for choosing a small number of relevant scenarios that combine both vulnerability and diversity. The paper applies the method to a real case involving climate resilient infrastructure for three African river basins (Volta, Orange and Zambezi). Introducing selection criteria in a stepwise manner helps examine how different criteria influence the choice of scenarios. The results suggest that combining vulnerability- and diversity-based criteria can provide a systematic and transparent method for scenario selection.

1. Introduction

Energy and environmental change planning and assessments at the local, regional, and global scales often use scenarios (Rounsevell and Metzger, 2010). For example, the Special Report on Emissions Scenarios (SRES) provides a well-known and much used scenario set commissioned by the Intergovernmental Panel on Climate Change (IPCC) (Nakicenovic et al., 2000). The SRES scenarios are explorative storylines describing future possible societies and associated greenhouse gas emissions pathways. New scenarios called Representative Concentration Pathways (RCPs; van Vuuren et al., 2011) and Shared Socio-economic Pathways (SSPs; O'Neill et al., 2015) have now replaced the SRES scenarios. The SRES, RCP, and SSP scenarios were all chosen through processes that relied largely on expert judgment. In this paper we propose a new computer-aided approach for choosing scenarios for environmental research and policy. This approach combines two perspectives on scenario development: scenarios for illuminating vulnerabilities of proposed policies and scenarios that span a diverse range of futures.

The scenario literature offers several useful taxonomies useful for organizing and comparing the many approaches for developing and using scenarios (see e.g. Bradfield et al., 2005; Börjeson et al., 2006; Bishop et al., 2007). Here it proves useful to highlight two approaches, *Intuitive Logics* and *Morphological Analysis*, which help contextualize important features of the vulnerability and diversity approaches of interest in this paper.

Intuitive Logics (Kahn and Wiener, 1967; Wilkinson et al., 2013) provides the most widely used technique for developing scenarios in environmental research. While there exist many variants of this school of thought, most include thre key elements: a decision the scenarios are meant to inform, identification of a small number of key driving forces, and storylines (Lempert, 2013). In this primarily qualitative approach, practitioners compile a list of driving forces in the external environment that may affect the decisions. Using expert judgement, practitioners then select a small number (often two) of the most important driving forces using a pair of criteria: importance to the decision and the degree of uncertainty. Each driving force generally takes on one of a small number of values (often two, e.g. 'high' and 'low') – that are then used to define a small set of scenarios (often four). Intuitive Logics seeks a small set

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of scenarios so users can more easily consider and compare them. The driving forces are also used to help craft a narrative for each scenario that helps enhance their communicative power. Intuitive Logics generates scenarios consistent with a typical definition, such as that offered by the Millennium Ecosystem Assessment, which describes a scenario as a "plausible and often simplified description of how the future may develop, based on a coherent and internally consistent set of assumptions about key driving forces" (Millennium Ecosystem Assessment, 2005, 214).

Morphological Analysis exemplifies a different approach for generating a different type of scenario (Zwicky, 1969; Von Reibnitz, 1988, Gausemeier et al., 1998; Ritchey, 2006; Scholz and Tietje, 2002; Tietje, 2005). The aim of Morphological Analysis is to address multi-dimensional, non-quantifiable problems by explicitly exploring all the many combinations of many 'uncertainties' (cf. 'driving forces' above) that can each take an arbitrary number of 'states' (cf. 'values' above). The analysis then eliminates the inconsistent state combinations using a cross consistency analysis and retains the rest. Morphological Analysis thus generates many 'scenarios', each consisting of one of the plausible combinations of the many uncertainties.

Computer aided methodologies provide the foundation for Morphological Analysis (Gordon and Hayward, 1968) and have also been employed to help choose scenarios at least since the 1970s, for instance within the French school *La Prospective* (Godet, 2000). Such computer-aided methodologies have been widely used in technological forecasting, but have to a large degree been left unnoticed by the environmental research community, which tends to employ Intuitive Logics-based methods. One notable example where computer aided techniques *have* been used in environmental research is the 'story and simulation' (SAS) approach, where narrative storylines are used as inputs to quantitative modeling e.g. of climate change impacts (Alcamo, 2001, 2008). But, in SAS computer techniques enter only *after* expert judgment has identified the scenarios and their storylines. Only a few examples exist in which computer aided techniques have been utilized in environmental research to identify narrative scenarios (see e.g. Schweizer and Kriegler, 2012; Schweizer and O'Neill, 2014; Cervigni et al., 2015, Groves et al., 2013).

This paper focuses on computer-aided methods for identifying *exploratory scenarios* for energy and environmental research and decision-making. In the terminology of Börjeson et al. (Börjeson et al., 2006), exploratory scenarios ask the question "what might happen?" and are typically used for cases, often at longer timeframes, for which the future is less predictable. Since in general an unlimited number of events might happen, a key challenge with using exploratory scenarios is choosing a set of scenarios sufficiently small to be manageable yet sufficiently well-chosen to avoid missing plausible future events that would prove relevant to the purposes of the analysis. For instance, energy and environmental decision support applications often require only a small number of scenarios because users can pay close attention to only a handful. In addition, subsequent analysis conducted with the scenarios, for instance evaluating the performance of policies, may create computational constraints that also limit the number of scenarios that can be considered. However, a limited number of scenarios can also exclude futures decision makers might find important to consider.

This paper addresses this challenge by combining two computer-aided approaches for selecting energy and environmental scenarios. The first approach selects scenarios that *illuminate vulnerabilities* of proposed policies. This vulnerability-based approach uses simulation models to explore the performance of policies over a wide range of futures and then chooses a small number of scenarios that best distinguish those futures in which a policy meets and misses its goals (Groves and Lempert, 2007; Bryant and Lempert, 2010). The second approach selects scenarios that are *diverse* by identifying a small set of scenarios that best span a wide a range of futures (Carlsen et al., 2016).

Both approaches begin with a large number of plausible futures, often generated by simulation models, similar to scenarios in the Morphological Analysis sense of the term. The diversity-based approach then uses optimization algorithms to choose a small set of such scenarios that best represents the range of plausible futures. In contrast, the vulnerability-based approach uses statistical algorithms to identify clusters of futures meant to be analogous to scenarios in the Intuitive Logics sense of the term. As described in Section 2.3, combining these two previously distinct yet complementary approaches provides useful and important synergies. In joining these two approaches, this paper offers an innovative way of choosing a small and manageable number of relevant scenarios based on both vulnerability and diversity. This paper demonstrates the approach in a test case, and suggests how it could be widely useful in many applications.

The next section defines the characteristics of the scenario vulnerability and diversity approaches and discusses the relationship between them. Section 3 applies the proposed approach to a real case involving climate resilient infrastructure for three African river basins (Volta, Orange and Zambezi). Section 4 concludes with pros and cons of the proposed combined approach, possible applications as well as possible extension including consistency-based approaches for systematic scenario generation, and an outlook for future research.

2. Methods

Why is it beneficial to combine a vulnerability approach and a diversity approach when identifying small sets of policy relevant scenarios? In order to answer this question, we first need to describe the two methodological building blocks and highlight some key similarities and differences.

2.1. Choosing scenarios that illuminate vulnerabilities

Scenarios can be chosen to highlight the choice among alternative policy options. For instance, if an organization has an existing plan, scenarios might be chosen to stress-test that plan to identify futures in which the plan may not meet its goals. If an organization is choosing among alternative plans, scenarios might be selected to help choose the plan that seems most robust (van der Heijden, 1996). Many scenario planning exercises ultimately have this type of goal. For instance, Intuitive Logics pioneer Peter Schwartz's guide to developing scenarios (1996) begins with steps that identify key decisions and then lists key factors which might influence the decisions' success or failure. While many Intuitive Logics exercises are qualitative, quantitative methods such as the vulnerability-based methods discussed in this paper can help identify scenarios that seem particularly relevant to choices decision-makers face. As one advantage over qualitative approaches, quantitative methods can help make the choice of scenarios more reproducible and traceable, more connected to decision, less ambiguous, less seemingly arbitrary and biased (Parker et al., 2015).

In particular, the concept of choosing scenarios that illuminate vulnerabilities of proposed policies (Groves and Lempert, 2007; Bryant and Lempert, 2010; Lempert, 2013) provides one important example of such a quantitative approach to scenario selection. This *Robust Decision Making* (RDM) (Lempert et al. 2003; Lempert and Collins, 2007) process begins with a computer simulation model that projects the performance of one or more policy options,