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Discovering plausible energy and economic futures under global change using multidimensional scenario discovery☆

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A B S T R A C T

The use of scenarios has proven valuable for global change analysis as a means for organizing and communicating information about uncertain future socioeconomic conditions. A small group of well-defined scenarios can provide a set of standard reference cases for assessing the performance of candidate policies under alternative futures. However, traditional methods of defining scenarios may yield storylines that do not align well with the capabilities of downstream models. It can also be difficult to assess whether the number and scope of constructed scenarios most effectively cover the space of possible outcomes. Model-based methods of 'scenario discovery' have recently been proposed that apply statistical data-mining algorithms to a large number of model simulations to identify regions of the stochastic parameter space that lead to unacceptable policy performance. These regions then delineate practically relevant and internally consistent 'discovered scenarios'. To distinguish 'acceptable' from 'unacceptable' policy outcomes, existing methods require pre-specification of a threshold value on a single performance metric. We believe this requirement may present a barrier when decision-makers hold differing views on the relative importance of multiple policy objectives. Therefore, we describe a scenario discovery method that is multidimensional in the outcome space, thus precluding the need for users to agree on a single performance threshold or set of tradeoff weights. We demonstrate application of our approach to the results of ENGAGE, an agent-based model (ABM) of economic growth, energy technology, and carbon emissions. We believe that scenario discovery can add particular value to agent-based modeling, as ABMs typically generate a wider array of possible futures than aggregate-scale models. For this reason, a systematic method for sorting through the many stochastic model simulations to identify policy vulnerabilities and opportunities is essential. We conclude by discussing how our methodology might be applicable to the development of socioeconomic scenarios under the 'representative concentration pathways' (RCP) framework.

1. Introduction

In integrated global change modeling, deep uncertainty concerning the interactions between socioeconomic, technological, and environmental conditions is typically addressed through scenario analysis (Riahi et al., 2007). A scenario can be thought of as a "coherent, internally consistent, and plausible description of a possible future state of the world" (McCarthy et al., 2001). By illuminating the span of possible futures, consideration of diverse scenarios has the potential to reduce decision-maker overconfidence, identify the factors to which policy performance might be most sensitive, and promote consideration of a wider range of options (Groves and Lempert, 2007).

To date, the specification of scenarios has typically followed a sequential, piecewise process. First, a set of qualitative storylines are developed, which are then each converted to a plausible set of exogenous inputs, such as population growth, technological development, or fuel cost changes (de Vries and Peterson, 2009). A model is then run for each scenario to provide projections of key system variables several decades or centuries forward. In some cases, these simulations are further elaborated using formal sensitivity analysis (van Vuuren et al., 2008) or participatory techniques (Shaw et al., 2009; Leenhardt et al., 2012).

The Special Report on Emissions Scenarios (SRES; Nakicenovic and Swart, 2000) is an instructive example of the sequential process. Largely following the 'scenario axis' method popularized

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by Schwartz (1991), it followed the quintessential procedure: (i) convene a panel of experts to identify significant driving forces, (ii) formulate a set of scenario storylines which apparently span the range of plausibility, and (iii) use these storylines to create detailed internally consistent futures. In the case of SRES, four storylines were developed and used to specify future trajectories of population, economic output, and technological change in the energy system. The trajectories then serve as exogenous input to integrated assessment models (IAMs), resulting in model projections of energy use, technology choice, greenhouse gas (GHG) emissions, and global temperature change, conditional on particular policy options. These model outputs can themselves be used in further downstream applications of more detailed climate models and impact-adaptation-vulnerability (IAV) studies.

A consequence of scenario generation in the sequential style of SRES is that considerable separation may exist between the driving force identification process and the use of storylines in downstream models and analyses. Scenario storylines often contain implicit descriptions of structural shifts, such as changes in technologies or societal values, which are then used in IAMs with methodologies that are often not flexible or comprehensive enough to adequately engage the original storyline (the PoleStar model (Raskin et al., 2010) is a notable exception). Thus, the intent of the scenario storyline is ultimately obscured as results are passed to downstream applications. Additionally, it is difficult to create scenario storylines that are sufficiently dispersed yet small in number, and not perceived to be biased by the expert development panel. Contention has also remained whether probabilities should be assigned to the projected outcomes and as to how results should be used to support decision making. Experience among the modeling community has indicated that problems with the scenario axis method often hinder the effective use of scenarios (Moss et al., 2010; Parson et al., 2007).

An alternative to pre-defining scenarios for subsequent use in typically 'top-down', aggregate-scale IAMs is to couple probabilistic simulation models with exploratory methods for identifying scenarios that arise inherently from an ensemble of model simulations (Robalino and Lempert, 2000). While many types of models can be used in this approach, agent-based models (ABMs) may represent a particularly well-suited match. Rather than focusing on the identification of optimal outcomes, agent-based modeling is primarily concerned with the evolution of large-scale properties that 'emerge' from lower-level behavior (Miller and Page, 2007). ABMs represent the world as made up of heterogeneous, boundedly rational agents who act in their own interests and interact with each other and the surrounding environment according to characteristic protocols of communication and decision making. Consequently, ABMs have the potential to represent complex system properties and generate a wider array of plausible storylines than more traditional methodologies for scenario generation (Smajgl et al., 2011). Since technological improvement is often critical to future trajectories, there is also substantial potential to leverage the progress that has been made on modeling the dynamics of technological innovation using ABMs (Dosi et al., 2010; Safarzyska and van den Bergh, 2010).

The exploratory approach to generating scenarios involves searching and visualizing model projections to first identify relatively distinct modes of behavior that, by virtue of having been generated by a logical model, are inherently internally consistent (Bankes, 1993). These behavioral modes, which for practical purposes are simply groups of simulation results that have similar characteristics, then become candidate scenarios. Important scenario driving forces are then determined by relating candidate scenarios to the corresponding stochastic model input and parameter values that generated them. Sets of model simulations subject to similar driving forces and with similar future projections then become final 'discovered' scenarios (Bryant and Lempert, 2010). As compared to the scenario axis method, scenarios generated using an exploratory model-based approach employ assumptions, scales, and parameter values that are fundamentally linked, thus providing a clear path to the development of internally consistent storylines.

The visualization and statistical techniques appropriate for scenario discovery depend on the policy questions being asked and the characteristics of the model simulations. For example, in the context of renewable energy, a decision-maker might want to know not only what is the expected net benefit of a specific policy measure, such as imposition of a renewable portfolio standard, but also what specific socioeconomic or technological developments might lead the policy to fail to meet its performance goals (e.g. by imposing unacceptably high economic costs). Bryant and Lempert (see Bryant and Lempert, 2010; Groves and Lempert, 2007; Lempert et al., 2006) propose a scenario discovery method to address such types of questions. The method involves pre-specifying a threshold value on a performance metric (e.g. expected cost or regret) that distinguishes between "acceptable" and "unacceptable" outcomes. A statistical data-mining algorithm is then used to identify the values of uncertain model parameters that best predict the occurrence of unacceptable outcomes.

We believe there is value in generalizing Bryant and Lempert's (see Bryant and Lempert, 2010; Groves and Lempert, 2007; Lempert et al., 2006) scenario discovery method to allow for interactive selection of the performance criteria used to delineate candidate scenarios. We would also like for these criteria to be able to accommodate multiple threshold levels over multiple metrics. Such a generalization will be especially useful when there are multiple attributes used to evaluate future policy outcomes (e.g., economic cost and environmental benefit) and there is not general agreement among stakeholders on how these attributes should be combined into a single metric. In this paper, we describe a method for multidimensional scenario discovery that first uses hierarchical clustering of model simulations to identify groups with similar outcomes over multiple attributes. These serve as candidate scenarios that in a second step are further refined using classification and regression tree (CART) analysis to identify common scenario drivers. We demonstrate the overall approach through application to the results of ENGAGE, an evolutionary agent-based model of economic growth, energy technology, and carbon emissions (Gerst et al., 2013). To make the presentation of the scenario discovery method concrete, in the next section we first provide an overview of the ENGAGE model and its key parameters and outputs. Description of our scenario discovery method then follows in the third section, while Section 4 describes the nature of the ENGAGE model simulations used in our study. Section 5 presents the results, which are then discussed in Section 6.

2. Model description

2.1. Model overview

As described in detail by Gerst et al. (2013), ENGAGE is based on the ABM of endogenous growth and business cycles developed by Dosi et al. (2010). The model economy is composed of two types of actors - firms and workers - who observe their environment and the behavior of other actors and make boundedly rational decisions. In the model of Dosi et al., firms are divided into two types, capital-good and consumer-good firms. Capital-good firms produce machines that are sold to consumer-good firms, which then use the machines to produce homogenous consumer goods. Workers sell their labor to firms in exchange for the market wage and use all of their income to buy consumer goods.

With ENGAGE, we have modified the model of Dosi et al. by adding energy attributes and a simplified energy system, including energy technology and production firms (Fig. 1). Each energy technology firm produces one type of stylized energy production technology—either 'carbon-heavy', 'carbon-light', or 'carbon-free'—and undertakes research and development (R&D) in order to improve the unit