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Dynamic scenario discovery under deep uncertainty: The future of copper

Jan H. Kwakkel [a,*], Willem L. Auping [b], Erik Pruyt [a]

[a] Faculty of Technology, Policy & Management, Delft University of Technology, Delft, The Netherlands
[b] The Hague Centre for Strategic Studies, The Hague, The Netherlands

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ABSTRACT

Scenarios are commonly used to communicate and characterize uncertainty in many policy fields. One of the main challenges of scenario approaches is that analysts have to try and capture the full breadth of uncertainty about the future in a small set of scenarios. In the presence of deep uncertainty, this is even more challenging. Scenario discovery is a model-based technique inspired by the scenario logic school that addresses this challenge. In scenario discovery, an ensemble of model runs is created that encompasses the various uncertainties perceived by the actors involved in particular decision making situations. The ensemble is subsequently screened to identify runs of interest, and their conditions for occurring are identified through machine learning. Here, we extend scenario discovery to cope with dynamics over time. To this end, a time series clustering approach is applied to the ensemble of model runs in order to identify different types of dynamics. The types of dynamics are subsequently analyzed to identify dynamics that are of interest, and their causes for occurrence are revealed. This dynamic scenario discovery approach is illustrated with a case about copper scarcity.

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1. Introduction

Scenarios provide a commonly used means to communicate and characterize uncertainty in many decision support applications. There exists a plethora of scenario definitions, typologies, and methodologies [1,2]. A distinction can be made between the *La Prospective* school developed in France, the Probabilistic Modified Trends school originated at RAND, and the Intuitive Logic school typically associated with the work of Shell [2]. In the evaluative literature, one of the reported problems of traditional scenario approaches is that they often struggle in case of problems that involve a variety of actors with quite diverse world views [3] or when there is a lacking consensus [4]. Scenario approaches also struggle with anticipating rare events [5] and grapple with the multiplicity of plausible futures [6]. The challenge of traditional scenario approaches is that analysts have to try and capture the full breadth of the uncertainty about the future in a small set of scenarios that need to be intelligible and useful to both the actors involved in the scenario development process and analysts supporting this process [7–9]. Developing or identifying a handful of scenarios, that fully represent all plausible futures is difficult. Communicating, and using more than a handful of representative scenarios is equally difficult and may even be counterproductive [9]. The intuitive logic school addresses these problems through the identification of the factors that are both highly uncertain and can have a profound impact on the decision problem at hand [8]. However, this works mainly if the group of involved actors is relatively small, their interests and concerns are known, and overlap to a certain extent [2]. Moreover, how to best represent the diversity contained in all the uncertain factors in a small set of scenarios, is a continuing challenge [10].

Recently, an approach called scenario discovery [7,10,11] has been put forward as a technique that can be used for developing scenarios for problems that involve a large number of actors with quite diverging world views and values and where there are many uncertain factors. Scenario discovery is a model driven approach that builds on the intuitive logic school [7]. Scenario

* Corresponding author.
E-mail addresses: J.H.Kwakkel@tudelft.nl (J.H. Kwakkel), willemAuping@hcss.nl (W.L. Auping), E.Pruyt@tudelft.nl (E. Pruyt).

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discovery builds on earlier work on using models for decision making under deep uncertainty [12–14]. It starts from an ensemble of model runs that is analyzed in order to identify runs that are of particular interest. Next, these runs of interest are analyzed to reveal the combinations of factors responsible for generating them. The documented cases of scenario discovery have used a single model with a small set of uncertain parameters as the basis for generating the ensemble of runs. For example [7], uses a model with 8 uncertain parameters, and [10] uses a model with 20 uncertain parameters, and the identification of interesting runs in both cases is based on the terminal values of each individual run of outcome indicators related to policy performance [7,10].

In this paper, we extend the scenario discovery approach conceptually, technically, and practically. Conceptually, we understand scenarios not as states of the world but as developments over time. Technically, this implies that the machine learning techniques usually applied in scenario discovery cannot be applied straightforwardly. To overcome this problem, we use time series clustering for the identification of sets of behaviors over time, thus transforming time series results to scalar values that can be used as input to the various machine learning techniques that can be used for scenario discovery. Practically, we extend scenario discovery by working with two structurally distinct models that share only a subset of the uncertain factors, and jointly cover significantly more uncertain parameters than earlier applications of scenario discovery. These practical extensions pose additional challenges in the design of the computational experiments and the analysis of the results.

To illustrate our extended scenario discovery approach, we apply it to the problem of copper scarcity. There has been a growing attention to mineral and metal scarcity, but this attention has been focused mainly on lithium, rare earth metals and other metals characterized by supply risks due to the limited number of countries where it is mined. However, bulk metals can also suffer from scarcity, as evidenced by the copper price which has been on a high level since 2005 [15], resulting in phenomena like the theft of copper wiring. Crisis behavior in the copper market may have profound impacts on society beyond increased copper theft, and may be particularly worrisome with regard to a transition towards more sustainable energy systems [16]. The main aim of the case was therefore to identify the various ways in which the copper system – composed of supply, demand, recycling, and substitution – could evolve, the kinds of dynamics that could occur, the undesirable price dynamics, and the causes for their occurrence.

The physical side of the copper system is well documented [e.g. 17,18] and does not contain much uncertainty. However, with respect to the way in which demand should be represented, there are profoundly diverging views: there are those who argue that copper demand should be modeled at a high level of aggregation as a function of world population, while others argue that one should use a bottom up approach from the various types of usages to the overall demand [19–21]. As argued by Cole, "whether a 'top-down' or 'bottom-up' approach is chosen, however, may affect the results. Simple recursive calculation of global or regional aggregates broken down by sector often gives surprisingly different results from systematically building up the global or regional aggregates from the sector or subsector levels" [22]. Other sources of uncertainty are the development of the ore grade [17,23], the impacts of substitution behavior [24], and various geopolitical developments, such as the growing copper demand in developing economies [17,25]. The various uncertainties are captured in two distinct simulation models. One represents a bottom up modeling of demand, while the other represents a top down modeling of demand. The supply system is essentially the same in both models. The behavior of these models is explored across a wide range of parametric uncertainties using Latin Hypercube Sampling. The results are clustered using a time series clustering approach, and subsequently analyzed using the patient rule induction method (PRIM) [26], a particular machine learning technique. Exemplars of undesirable dynamics are identified, and their conditions for occurring derived.

In the next section, we review the current scenario discovery approach and outline where and how we have extended it to cope with dynamics over time. In Section 3, we illustrate this modified scenario discovery approach through the case of copper scarcity. Section 4 discusses these results from a methodological point of view. Section 5 presents the main conclusions.

2. Dynamic scenario discovery

Scenario discovery addresses problems encountered when trying to develop model-based scenarios for problems that involve a large number of actors with diverging world views and values, or that are characterized by a very large number of uncertain factors. Typical for such problems is that the analysts do not know, or the parties to a decision cannot agree on (1) the appropriate conceptual models that describe the relationships among the key driving forces that shape the long-term future, (2) the probability distributions used to represent uncertainty about key variables and parameters in the mathematical representations of these conceptual models, and/or (3) how to value the desirability of alternative outcomes [14]. This is also called decision making under deep uncertainty, or severe uncertainty [14,27]. In the presence of a lack of knowledge or disagreement related to the model representation of a system and the evaluation of outcomes, enumeration of multiple alternatives for how (aspects of) the system works or are to be parameterized and how to value outcomes may still be possible, without being able to rank order these alternatives in terms of how likely or plausible they are judged to be [28].

2.1. Exploratory modeling and analysis

Scenario discovery builds on earlier work on using models for decision making under deep uncertainty [12–14]. Under deep uncertainty, it is not possible to develop a single model that accurately represents the system of interest. Exploratory modeling and analysis (EMA) [12] provides an alternative way of using the available information, data, and knowledge. An ensemble of models, consistent with the available knowledge, data, and information is developed. A single model run drawn from this

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