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Exploratory Modeling and Analysis, an approach for model-based foresight under deep uncertainty

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ABSTRACT

Exploratory Modeling and Analysis (EMA) is an approach that uses computational experiments to analyze complex and uncertain issues. It has been developed mainly for model-based decision support. This paper investigates the extent to which EMA is a promising approach for future oriented technology analysis (FTA). We report on three applications of EMA, using different modeling approaches, in three different technical domains. In the first case, EMA is combined with System Dynamics (SD) to study plausible dynamics for mineral and metal scarcity. The main purpose of this combination of EMA and SD is to gain insight into what kinds of surprising dynamics can occur given a variety of uncertainties and a basic understanding of the system. In the second case, EMA is combined with a hybrid model for airport performance calculations to develop an adaptive strategic plan. This case shows how one can iteratively improve a strategic plan through the identification of plausible external conditions that would cause the plan to perform poorly. In the final case, EMA is combined with an agent-based model to study transition dynamics in the electricity sector and identify crucial factors that positively and negatively affect a transition towards more sustainable functioning of the electricity sector. This paper concludes that EMA is useful for generating foresights and studying systemic and structural transformations despite the presence of a plethora of uncertainties, and for designing robust policies and plans, which are key activities of FTA.

1. Introduction

Future-oriented technology analysis (FTA) is understood as an "umbrella" label for various approaches to explore future developments, including technology forecasting, technology intelligence, future studies, foresight, and technology assessment [1]. In their own ways each of these approaches is used for analyzing technological developments and their potential consequences. Technology refers both to physical artifacts as well as to social practices that specify how these artifacts can be used. Thus, technological systems can be decomposed in the physical components as well as the social components, including institutions. The various fields covered by the umbrella term FTA have at their disposal a wide variety of methods, techniques, and approaches. A subset of these approaches relies, at least in part, on mathematical and computer models.

The reason for using models might be understood in light of the rise of Newtonian mechanics and its success in predicting a wide array of different phenomena [2]. It brought together the celestial realm and the sub-lunar realm in a single explanatory framework [2,3]. Moreover, it showed that theory was 'a far more effective means than observation for precisely characterizing complex orbital motions […] physical theory gained primacy over observation for purposes of answering specific questions about the world' [3]. Over the course of the eighteenth century, Newtonian mechanics was interpreted by Laplace as a clockwork universe after the success of the theory of gravity in accounting for complex deviations from Keplerian motion became fully evident [2,3]. If the mechanisms of the clock are known, any future state of the clock can be predicted. Similarly, if the

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mechanisms underlying a phenomenon are perfectly known, one could predict the future development of this phenomenon. With the rise of computers and user friendly software, more and more mechanisms can be, and are, codified into computer models.

However, the use of models to make predictions can be seriously misleading if there are profound uncertainties. The solar system of planets is a relatively small system – the sun and the eight planets – and can be very well observed, and thus its behavior can be predicted with great accuracy. However, for many other phenomena, such as the world's climate, or systems in which humans are involved, the situation is different. In these cases, there are many components and mechanisms that interact in a variety of ways, and the system can only partly be observed. The use of predictive models for such systems is problematic. There have been scientists who have realized this. Some claim "the forecast is always wrong" [4], others say "all models are wrong" [5], and yet again others qualify arithmetic for such systems as useless [6]. Such comments raise the question whether models can be used at all in decision-making under uncertainty.

In their agenda setting paper on FTA, Porter et al. [1] note that "there are many irreducible uncertainties inherent in the forces driving toward an unknown future beyond the short term and predictions need not be assumed to constitute necessary precursors to effective action". In other literature, this is called deep uncertainty [7,8], or severe uncertainty [9]. It can be understood as a situation where one can incompletely enumerate multiple possibilities without being able or willing to rank order the possibilities in terms of how likely or plausible they are judged to be [8].

There is a need for model-based support for the design of robust strategies across this spectrum of irreducible uncertainties. The RAND Corporation developed a technique called Exploratory Modeling and Analysis (EMA) tailored to this. EMA aims at offering decision support even in the face of many irreducible uncertainties, by systematically exploring the consequences of a plethora of uncertainties – ranging from parametric uncertainties (e.g. parameters ranges), over structural uncertainties (e.g. different structures and models), to method uncertainties (e.g. different modeling methods) – using computational models as scenario generators.

This paper explores the potential of EMA for FTA. It thus explicitly addresses one of the FTA challenges identified by Porter et al. [1] by assessing how EMA could contribute to adaptive foresight [10] under deep uncertainty. Particular attention is given to the potential of EMA in offering decision support for shaping systemic and structural transformation.

The paper is structured as follows. Section 2 provides more background on EMA. To further elucidate what EMA is and in order to assess the potential of EMA for FTA, three case studies are reported in Section 3. Section 4 is a discussion of the results of these cases and their implications for FTA. Section 5 contains the conclusions.

2. Exploratory modeling and analysis

Various scientific fields including the environmental sciences, transportation research, economics, and the political sciences, are involved in providing model-based decision support. In these various fields, people are grappling with the treatment of deep and irreducible uncertainty while using models. A common theme across these fields appears to be a shift away from predictive model use towards more explorative model use [6,11,12]. Exploratory Modeling and Analysis (EMA) is a research methodology that uses computational experiments to analyze complex and uncertain systems [12,13]. Porter et al. [1], in their agenda setting paper on FTA, explicitly mention EMA as being of potential interest to FTA. To our knowledge, the potential of EMA for FTA has however not been investigated yet. This paper can be seen as an attempt to do so.

EMA can be useful when relevant information exists that can be exploited by building models, but where this information does not allow specifying a single model that accurately describes system behavior. In this circumstance, models can be constructed that are consistent with the available information, but such models are not unique. The available information is consistent with a potentially infinite set of plausible models, whose implications for potential decisions may be quite diverse. A single model run drawn from this set provides a computational experiment that reveals how the world would behave if the various guesses this single model makes about the various irreducible uncertainties are correct. By conducting many such computational experiments, one can explore the implications of the various guesses. EMA is the explicit representation of the set of plausible models, the process of exploiting the information contained in such a set through a large number of computational experiments, and the analysis of the results of these experiments [12,13].

EMA is not focused narrowly on optimizing a (complex) system to accomplish a particular goal or answer a specific question, but can be used to address 'beyond what if' questions, such as "Under what circumstances would this policy do well? Under what circumstances would it fail?", and "what is the range of plausible future dynamic developments of a phenomenon of interest? Under what circumstances can we expect which dynamic developments?" Because of this focus, EMA stimulates 'out of the box' thinking and can support the development of adaptive plans or policies.

EMA is first and foremost an alternative way of using the available models, knowledge, data, and information. In making policy or planning decisions about complex and uncertain problems, EMA can provide new knowledge, even where strict model validation is impossible. For example, EMA can be used for existence proofs or hypothesis generation, by identifying models that generate atypical or counterintuitive behavior. Knowing that a system can exhibit such behavior can change the debate or open up new directions for the design of targeted solutions. Another example is the case where there is ample data available, but also disagreement or uncertainty about which data to use. EMA can be used to identify the extent to which the choice of data influences the model outcomes. Instead of debating the choice of the right data, the debate can then shift to the development of policies or plans that produce satisfying results across the alternative sets of data. Other possible uses of EMA include the identification of extreme cases, both positive and negative, in order to get insight into the bandwidth of expected outcomes, and the identification of conditions under which significant shifts in performance can be expected. All these examples rely on the fact