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How to do structural validity of a system dynamics type simulation model: The case of an energy policy model

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A B S T R A C T

System dynamics based simulation models are becoming increasingly popular in the analysis of important energy policy issues including global warming, deregulation, conservation and efficiency. The usefulness of these models is predicated on their ability to link observable patterns of behavior of a system to micro-level structures. This paper argues that the structural validity of the simulation model—right behavior for the right reasons—is a stringent measure to build confidence in a simulation model regardless of how well the model passes behavior validity tests. That leads to an outline of formal structural validity procedures available but less explored in system dynamics modeling 'repertoire'. An illustration of a set of six tests for structural validity of a system dynamics model for energy policy analysis follows. Then using Theil inequality statistics, the behavior validity of the model is also tested. Finally, some conclusions on the increased appeal for simulation models for energy policy analysis and design are presented.

1. Introduction

Simulation models have been developed and applied to both operational problems and policy issues in energy sector. However, the need and the evaluation criteria of model validation differs for each case. For instance, in the case of operational problems, the results of a model can be accepted or rejected by exposing the results to a face validity test (Hermann, 1967; Emshoff and Sission, 1970; Zebda, 2002). In a face validity test, experts assess how the model and its results are close to the real system. Model solutions can be tested in real world environments: e.g., efficiency of the oil refinery can be enhanced under the recommended actions (Finlay and Wilson, 1987; Gass, 1983).

In contrast, the majority of policy models such as system dynamics (SD) type model and agent-based models are built for the analysis of policy, exploration of possible future scenarios, and management purposes (Gass, 1983; Sterman, 1984; Oliva, 2003; Scholl, 2001). Especially, researchers from SD community have found system dynamics modeling to be useful in energy policy domain. For instance, system dynamics models have been developed and applied to national energy policy evaluation (Ford, 1983; Naill, 1992; Qudrat-Ullah and Davidsen, 2001), investments and uncertainty (Ford, 1985), conservation policy analysis (Ford and Bull, 1989), effects of agents on utility performance (Geraphty and Lyneis, 1985), inter-fuel substitution in OECED-European electricity production (Moxnes, 1990), privatization of electricity industry (Bunn and Larsen, 1992; Bunn et al., 1997), and energy efficiency analysis (Dyner et al., 1995). These models are also able to link observable patterns of behavior of a system (e.g., global warming) to micro-level structure (e.g., stock of production capital) and decision making processes (e.g., Kyoto Protocols). Despite these relevant modeling strengths, the overall appeal of system dynamics modeling approach to the wider community of energy policy modelers is limited at best.

The purpose of this paper, therefore, is to (i) explore how structural validity testing might help in enhancing the overall validation and acceptance of a SD type simulation model and why structural validity is a stringent measure to build confidence in an SD type energy policy model, (ii) provide details on how formal validation procedures can help, and (iii) demonstrate, by examples, the application of these formal procedures to a system dynamics model of energy policy domain. It is hoped that energy policy modelers, as a result of our illustrations, will appreciate the usefulness of already existing but least explored tests in validation of energy policy models.

For the discussion of this paper, the model refers to an SD type simulation model. This paper is organized as follows. In Section 2, an argument that structural validity is a stringent measure to

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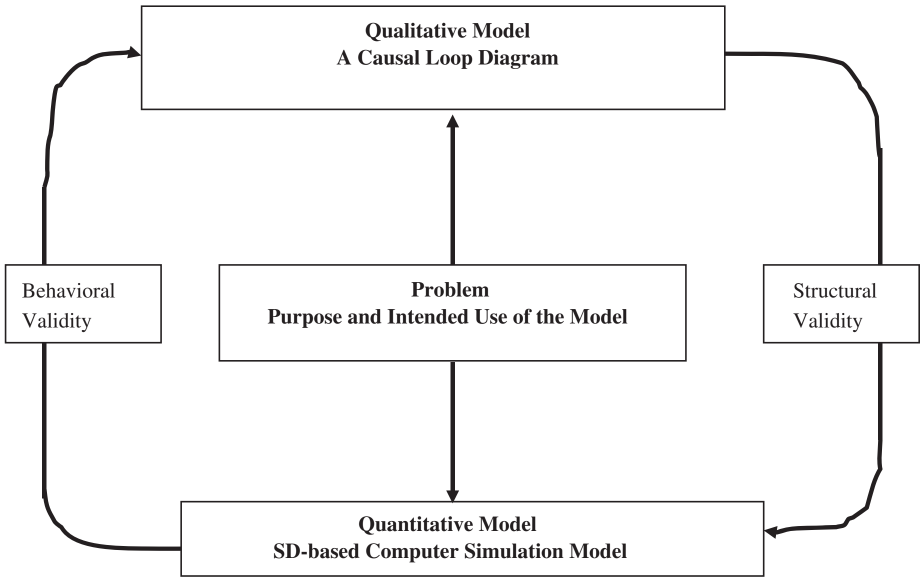

Fig. 1. A simplified view of SD modeling process and positioning of structural and behavioral validity.

build confidence in SD type models is established. Structural validity procedures are described in Section 3. Section 4 provides an illustration of structural validity tests. Concluding remarks are presented in Section 5.

2. Structural validity

From energy policy research perspective, modeling resolutions to important issues simply defy a face validity test. Instead, for policy models, the key issue in validation is deciding (i) if the model is acceptable for its intended use, i.e., does the model mimic the real world well enough for its stated purpose (Forrester, 1961; Goodall, 1972; Forrester and Senge, 1980; Zebda, 2002) and (ii) how much confidence to place in model-based inferences about the real system (Eberlein, 1989; Barlas, 1989, 1994; Curry et al., 1989; Van Horn, 1971; Sterman, 2000). In order to assess the theoretical content of a policy model, it is imperative to look at the modeling process itself. Therefore, before we could begin to illustrate the validation for SD models, it is crucial to examine SD modeling process first.

The appeal of SD models in the analysis of energy policy issues is due to their ability to link observable patterns of behavior of a system to micro-level structure and decision making processes. In order words, SD models are causal models (Barlas, 1989; Sterman, 2000). The crux of SD modeling process is to identify how structure and decision policies help generate the observable patterns of behavior of a system and then identified structures and decision policies be implemented. Therefore, the identification of the appropriate structure is the first step in establishing validity of an SD model. Once the structural validity of an SD model is sufficiently established, behavior validity—how well the model-generated behavior mimics the observed behavior of the real system—is assessed to achieve the overall validity of the model or to build confidence in the model (Eberlein, 1989; Gass, 1983; Sterman, 1984, 2000; Zebda, 2002). In fact the validation process becomes iterative: structural validity–behavior validity–structural validity. Since structural validity involves stakeholders of the model, modelers, clients, and policy researchers, we argue that structural validity is a stringent measure to build confidence in an SD model regardless of how well the model passes behavior validity tests.

In general, validation of SD models draws on two fundamental assumptions of SD modeling process: (1) SD models are built to fulfill a purpose, and (2) structure of the model drives its behavior (Forrester, 1961). SD modeling process begins with ‘conceptualization’ of the policy issue and produces a ‘quantitative computer simulation model’ for policy assessment and design. The purpose of the model informs the construction of both qualitative and quantitative model (Fig. 1).

Since its inception, SD has linked the validation of a model with its “purpose”. As Forrester emphatically sates that the validity of model should be judged by its suitability for a particular purpose and validity, as an abstract concept divorced from purpose, has no useful use (Forrester, 1961). This view of model validation is widely shared by other modelers and policy scientists (Barlas and Carpenter, 1990; Forrester and Senge, 1980; Holling, 1978; Overton, 1977).

Although SD modeling process is iterative in nature (Fig. 1), essence of an SD type model lies in how well the problem has been conceptualized and causal relationships are identified or the qualitative model is constructed. In fact, how well a simulation model represents the actual system is at the core of validation process of any type of simulation model (Law and Kelton, 2000). Moreover, it is the qualitative modeling stage that takes the temporal precedence over the quantitative modeling stage of any SD modeling endeavor: you have to have a conceptual model ready before any effort to realize a computer simulation model could ensue. At the qualitative modeling stage, focus is on (i) having appropriate representation of the problem, and (ii) identifying the causal relationships between the elements of the conceptual model. If problem is either misrepresented or the causal relationships in the model are faulty, model-generated data or model’s recommendations would simply be misleading. Therefore, structural validity: “right behavior for the right reasons” becomes the core of the SD modeling validation process (Barlas, 1989).

Moreover, model validation depends on the cultural context and background of the model builders and model users. It depends on whether one is an “observer” (e.g., an academic researcher) or an “operator”, e.g., a decision maker who must act without waiting for data of further analysis, (Greenberger et al., 1976). Nevertheless, involvement of stakeholders in the modeling process results in the increased credibility of the model