System Dynamics and Uncertainty

dr. Erik Pruyt

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Abstract

System Dynamics is often used for dealing with dynamically complex issues that are also uncertain. This paper reviews how uncertainty is dealt with in System Dynamics modeling, where uncertainties are located in models, which types of uncertainties are dealt with, and which levels of uncertainty could be handled. Shortcomings of System Dynamics and its practice in dealing with uncertainty are distilled from this review and reframed as opportunities. Potential opportunities for dealing with uncertainty in System Dynamics that are discussed here include (i) dealing explicitly with difficult sorts of uncertainties, (ii) using multi-model approaches for dealing with alternative assumptions and multiple perspectives, (iii) clearly distinguishing sensitivity analysis from uncertainty analysis and using them for different purposes, (iv) moving beyond invariant model boundaries, (v) using multi-method approaches, advanced techniques and new tools, and (vi) further developing and using System Dynamics strands for dealing with deep uncertainty.

Introduction

System Dynamics (SD) is used for studying the dynamics of, and for decision-making in the context of, dynamically complex issues, many of which are also uncertain. Uncertainty refers to the lack of knowledge about past, present, and future (Walker *et al.*, 2003). Surprisingly few system dynamicists explicitly refer to uncertainty, in spite of the fact that uncertainty and dealing with it has always been important in SD. That does not mean exemplary SD work under uncertainty does not exist. For example, Ford and colleagues explicitly address uncertainties in the long-term future energy system (Ford *et al.*, 1989; Ford and Bull, 1989; Ford, 1989, 1990). Recognizing from the start that many model parameters and variables were highly uncertain, uncertainty was defined and focused on using Latin Hypercube Sampling and statistical analysis of the outcomes. Interdependencies between important uncertain inputs were subsequently handled by incorporating extra-structural relationships, i.e. model structures to account for dependence between inputs, leading to another round of modeling, sampling, and analysis. They even tested the sensitivity of the outcomes to changes in the perspective/theory underlying the model. Almost on the side, it was concluded that intuition alone does not provide sufficient understanding (Ford, 1989). This is a major conclusion: for dealing with uncertainty in SD modeling, more than simulation and intuition is needed.

Other system dynamicists who explicitly refer to uncertainty acknowledge that it is omnipresent in real-world settings (Lyneis and Ford, 2007), that SD models almost always contain a large number of highly uncertain parameters and model formulations (Ford and Flynn, 2005; Moxnes, 2005), that all models are inevitably incomplete, incorrect, uncertain, wrong, and that our knowledge is limited (Sterman, 2002), but also that models allow to improve decision-making under uncertainty since models can easily be altered to represent different assumptions (Meadows, 1980). Several system dynamicists have therefore argued in favor of a more conscious, deeper and broader focus on uncertainty in SD. For example, it has been argued that SD models should be simulated over unusually wide ranges of changes in both parameters and structure since only a very wide range can reveal their inherent dynamics (Tank-Nielsen, 1980; Meadows *et al.*, 1982; Acharya and Saeed, 1996; Sterman, 2002), that practitioners must do a much better job of testing the robustness of conclusions to uncertainty in assumptions (Sterman, 2002), that the full power of SD for dealing with uncertainty and risk has not been tapped yet (Lyneis and Ford, 2007; Thompson and Duintjer Tebbens, 2008), and that there may be substantial benefits in more explicitly dealing with uncertainty in SD modeling (Pruyt, 2007; Duintjer Tebbens *et al.*, 2008).

The following questions are addressed in this paper in order to investigate these claims and what they mean for the SD field: How are uncertainties dealt with in SD modeling? Where are uncertainties located in SD models? Which types of uncertainties are, and should be, dealt with? Which levels of uncertainty are, and could be, covered with SD? Are there shortcomings in the way uncertainty is dealt with in SD and by SD practitioners? What are the opportunities to be seized or lessons to be learned for SD as it is practiced today? And could a SD approach for deeply uncertain issues be developed?

Some of these questions were previously investigated with various taxonomies of uncertainty. Pruyt (2007) used two taxonomies of uncertainty developed by van Asselt (2000) to analyze how SD practitioners handle different sources and types of uncertainty. Although both taxonomies proved useful for recognizing the existence of different sources and types of uncertainty and for identifying different approaches and techniques for dealing with uncertainty, they were also problematic in the sense that these taxonomies are not mutually exclusive nor collectively exhaustive. And the Authors (201x) located different SD approaches towards uncertainty in a levels of uncertainty taxonomy to distinguish strands of SD in terms of the level of uncertainty they could be used for. Although useful for that purpose, the levels taxonomy used there only focuses on a single dimension while uncertainty is a multi-dimensional concept. From these attempts as well as from an extensive review of the uncertainty literature, it was concluded that multiple taxonomies are useful for reviewing the way uncertainties are, and could be, dealt with in the SD field, but also that each of the extant taxonomies is insufficient and that alternative taxonomies are not mutually exclusive. In this article, the SD literature is therefore reviewed from multiple angles without clinching to taxonomies. The obvious drawback of this multi-angle approach is the unavoidable overlap.

First, the SD literature is reviewed to assess how uncertainties are explored or taken into account in SD modeling, where they are located in SD models, which types of uncertainty are dealt with, and the level of uncertainty SD could used for. From this multi-angle review of the SD literature, some shortcomings and opportunities for the SD field are distilled which are subsequently discussed. Finally, concluding remarks are made. Note that this paper does not address issue-specific uncertainties.

The full paper (including the body of the paper) is available upon request.

Conclusions

This paper reviewed, from four different angles, how uncertainties are dealt with in SD. We looked at: (*i*) the SD approach for dealing with uncertainty (in the process, through SA, and through multi-methods), (*ii*) the location of uncertainties in models (input, structural, methodological, and output), (*iii*) the types of uncertainties dealt with (lack of information, conflicting perspectives and values, indeterminacy, and variability), and (*iv*) the levels of uncertainty dealt with (marginal, shallow, medium, deep, and recognized ignorance).

From this review, the following was concluded. Some input uncertainties are traditionally dealt with in SD: some uncertain inputs are included in SD models and sensitivity to changes are tested. However, noise, surprises, and uncertain changes beyond the model boundary are not. And although it has been argued that structural and methodological uncertainties should be tested too, such tests are hardly performed or reported on in SD practice. Uncertainties, especially the more difficult ones, should thus be dealt with explicitly and in line with the characteristics of their real-world counterparts. Output uncertainty is traditionally dealt with in SD, e.g. by means of qualitative mode of behavior interpretations, but in a way that is rather unusual to outsiders of the field. And although robustness is argued to be important, in practice it is rarely thoroughly tested, i.e. over the entire uncertainty space. Uncertainty is nevertheless implicitly dealt with in traditional SD modeling throughout the modeling process, through inclusion of rich information, and through qualitative mode of behavior interpretations. The way in which dealing with uncertainty is embedded in the traditional SD process, is consistent and useful if computation is expensive, but also rather unusual – especially in an era of cheap computing power and advanced algorithms. The traditional approach for dealing with uncertainty could easily be misinterpreted by outsiders as one in which uncertainty is ignored and inaccuracy is valued. It therefore requires thorough explanation of how uncertainty is dealt with, each time it is employed. Moreover, in terms of SA as performed in the SD field, more should be done. SD should also be made appropriate for situations characterized by too much information, as well as with situations characterized by an unresolvable lack of information.

Many of these shortcomings could be remedied by embracing multi-model approaches, by explicitly dealing with uncertainties within and beyond model boundaries, by matching SD with complementary method(ologie)s, and by using advanced techniques and tools. For example, multi-model/multi-method approaches make it possible to deal with the most difficult uncertainties – such as those related to structures, boundaries, perspectives, contested knowledge claims, and methodological choices. Interestingly, it is not necessary to merge alternative models in order to find appropriate policies. Policies that are acceptable across models and other uncertainties often exist. The multi-model idea is not new: Bremer already suggested testing rival models/theories (Meadows *et al.*, 1982, p231). However, until recently, multi-model work was severely hindered by (*i*) the human weakness with regard to thinking in, and generating, multiple perspectives and hypotheses, (*ii*) the lack of sufficiently helpful methods and systematic procedures to support the development of alternative models/hypotheses, as well as (*iii*) the lack of sufficiently helpful methods, tools and techniques to simultaneously use multiple models, analyze their outcomes, and use them to design policies and test their robustness. Today, multi-model, multi-method, multi-policy simulation under deep uncertainty is feasible with commercial SD software in combination with existing open source scripting and analysis software.

A multi-model approach is useful for SA to semi-automatically test the sensitivity of base case model behavior to changes in assumptions, but even more so for UA to explore scenario spaces and assess policy effectiveness across uncertainty spaces. Since SA and UA serve different purposes and enable alternative approaches for dealing with different levels of uncertainty, it may be interesting, even necessary, to clearly distinguish between SA and UA and use them for their respective purposes. The potential of full-blown UA in SD is yet to be tapped: New methods, techniques, and tools have recently been developed or imported from complementary fields. When using them intelligently, they allow one to explore ensembles of uncertain dynamics in an insightful and transparent way. Some of these methods and techniques require more computing power, which is also available today.

Making a strict distinction between traditional SD versus ESDMA and SA versus UA may also solve another issue, namely the omission/inclusion of uncertain exogenous time evolutionary behavior: Traditional SD and SA could then be used for studying changes in purely endogenous dynamics without varying exogenous time evolutionary behavior, while ESDMA and UA could be used to study largely endogenous system dynamics with important exogenous uncertainties. The SD capacity to deal with uncertainty, for example about the future, may benefit from including uncertainties that vary over time. Sampling over broad sets of plausible time series or over endogenous parameters to generate broad sets of plausible behaviors, and testing and analyzing the influence of all sorts of surprises and exogenous behaviors on the behavior of largely endogenous models allows one to assess the response of largely endogenous systems to all sorts of uncertainties, including those beyond model boundaries.

Including broad sets and ranges of uncertainties, possibly using a multi-model approach, applying full-blown UA while refraining from base case interpretations and using machine learning techniques to explore the uncertainty-scenario spaces, would make SD suitable for dealing with issues that are characterized by deep uncertainty, not just medium uncertainty. Addressing deep uncertainty with model-based approaches requires the systematic exploration of different hypotheses related to model structure and inputs on the kinds of behavioral dynamics that can occur, directed searches, and robust policy design. Combining SD with EMA allows one to do so. And although the resulting SD strand –labeled ESDMA– is still being developed and does not promise to be easier than traditional SD, it is already feasible and open source tools are available for doing so. Some of these techniques and tools could be used to enhance the analytical capabilities of traditional SD modeling too.

Past hurdles for further embracing uncertainty in SD included the lack of appropriate methods, techniques and tools as well as the lack of sufficient computing power. These hurdles cease to exist today: ESDMA and other multi-methods that are needed to address aspects of uncertainty that SD has not traditionally focus on are now available and computing power is sufficiently cheap. This may open up SD to new uses, uncertain issues, and new communities.

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