System Dynamics and Uncertainty

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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.

References

Agusdinata D. 2008. Exploratory Modeling and Analysis. A Promising Method to Deal with Deep Uncertainty. PhD Thesis, Delft University of Technology, Delft, NL.

Acharya SR and Saeed K. 1996. An attempt to operationalize the recommendations of the 'limits to growth' study to sustain the future of mankind. *System Dynamics Review* **12**(4): 281–304.

Auping WL, Pruyt E, Kwakkel JH. 2012. Analysing the uncertain future of copper with three exploratory system dynamics models. In *Proceedings of the 30th International Conference of the System Dynamics Society.* St.-Gallen, CH, System Dynamics Society.

Auping, WL, Pruyt E, Kwakkel JH, Gijsbers G, Rademaker M. 2012b. *Aging: uncertainties and solutions. An exploration of scenarios, problems and solutions with respect to the affordability of societal aging.* No 2012/10. The Hague: The Hague Center for Strategic Studies.

Auping WL, Pruyt E, Kwakkel JH, Rademaker M. 2012a. *Futures for Copper: Exploring plausible copper price scenarios and how to act on them.* No 15/06/12. The Hague: The Hague Center for Strategic Studies.

Authors (201x). Radicalization under deep uncertainty: a multi-model exploration of activism, extremism, and terrorism. *System Dynamics Review.* Under review.

Bankes SC. (1992). *Exploratory modeling and the use of simulation for policy analysis.* RAND Note N-3093, RAND.

Bankes SC. 1993. Exploratory modeling for policy analysis. *Operations Research* **41**(3): 435–449.

Bankes SC. 2002. Tools and Techniques for Developing Policies for Complex and Uncertain Systems. In *Proceedings of the National Academy of Sciences of the United States of America* **99**(3): 7263–7266.

Bankes SC. (2009). Models as lab equipment: science from computational experiments. *Comput Math Organ Theory* **15**(1): 1–8.

Bryant BP, Lempert RJ. 2009. Thinking inside the box: A participatory, computer-assisted approach to scenario discovery. *Technological Forecasting & Social Change* **77**(1): 34–49.

Chen FF. 1983. A new kind of sensitivity testing in system dynamics modeling for sensitive results from aggregation assumptions. In *Proceedings of the 1st International Conference of the System Dynamics Society*, Chestnut Hill, MA, USA.

Clemson B, Tang Y, Pyne J, Unal R. 1995. Efficient methods for sensitivity analysis. *System Dynamics Review* **11**(1): 31–49.

Dangerfield BC, Fang Y, Roberts CA. 2001. Model-based scenarios for the epidemiology of HIV/AIDS: The consequences of Highly Active Antiretroviral Therapy. *System Dynamics Review* **17**(2): 119–150.

Duintjer Tebbens R, Thompson K, Huninck M, Mazzuchi T, Lewandowski D, Kurowicka D, and Cooke R. 2008. Uncertainty and sensitivity analyses of a dynamic economic evaluation model for vaccination programs. *Medical Decision Making* **28**(2): 182–200.

Eker S, Slinger JH, Yücel G. Investigating an automated method for the sensitivity analysis of functions. In *Proceedings of the 30th International Conference of the System Dynamics Society.* St.-Gallen, CH, System Dynamics Society.

Fiddaman TS. 2002. Exploring policy options with a behavioral climateeconomy model. *System Dynamics Review* **28**(2): 243–267.

Ford A. 1989. Asymmetry in energy system uncertainty. *IEEE Transactions on Systems, Man and Cybernetics* **19**(5): 1053–1059.

Ford A. 1990. Estimating the impact of efficiency standards on the uncertainty of the Northwest electric system. *Operations Research* **38**(4): 580–597.

Ford A. 1995. Simulating the controllability of feebates. *System Dynamics Review* **11**(1): 3–29.

Ford A, Amlin J, Backus G. 1983. A practical approach to sensitivity testing of system dynamics models. In *Proceedings of the 1st International Conference of the System Dynamics Society*, Chestnut Hill, MA, USA.

Ford A, Bull M. 1989. Using system dynamics for conservation policy analysis in the Pacific Northwest. *System Dynamics Review* **5**(1): 1–16.

Ford A, Bull M, Naill R. 1989. Bonneville's conservation policy analysis models. *Energy Policy* **15**: 109–124.

Ford A, Flynn H. 2005. Statistical screening of system dynamics models. *System Dynamics Review* **21**(4): 273–303.

Ford DN, Sobek DK. 2005. Adapting real options to new product development by modeling the second toyota paradox. *IEEE Transactions on Engineering Management* **52**(2): 175–185.

Forrester JW. 1961. *Industrial Dynamics.* MIT Press: Cambridge, MA.

Forrester JW. 1969. *Urban Dynamics.* MIT Press: Cambridge, MA; reprinted by Pegasus Communications: Williston, VT.

Ghaffarzadegan N, Lyneis J, Richardson GP. 2011. How small system dynamics models can help the public policy process. *System Dynamics Review* **27**(1): 22–44.

Graham AK. 1976. Parameter formulation and estimation in system dynamics models. *D-Memos* **D-2349-1**.

Graham AK, Ariza CA. 2003. Dynamic, hard and strategic questions: using optimization to answer a marketing resource allocation question. *System Dynamics Review* **19**(1): 27–46.

Hadjis A. 2011. Bringing economy and robustness in parameter testing: a Taguchi methods-based approach to model validation. *System Dynamics Review* **27**(4): 374–391.

Hamarat C, Kwakkel JH, Pruyt E. 2013. Adaptive robust design under deep uncertainty. *Technological Forecasting & Social Change* **80**(3): 408–418.

Hearne JW. 2010. An Automated Method for Extending Sensitivity Analysis to Model Functions. *Natural Resource Modeling* **23**(2): 107–120.

Hoekstra A. 1998. *Perspectives on Water: An Integrated Model-Based Exploration of the Future.* Utrecht: International Books.

Homer JB. 1993. A system dynamics model of national cocaine prevalence. *System Dynamics Review* **9**(1): 49–78.

Homer JB, Oliva R. 2001. Maps and models in system dynamics: a response to Coyle. *System Dynamics Review* **17**(4): 347–355.

Homer JB. 2013. The aimless plateau, revisited: why the field of system dynamics needs to establish a more coherent identity. *System Dynamics Review* **29**(2): 124–127.

Johnson S, Taylor T, Ford DN. (2006). Using system dynamics to extend real options use: Insights from the oil & gas industry. In *Proceedings of the 2006 Conference of the System Dynamics Society*, Nijmegen. System Dynamics Society.

Kunsch PL, Springael J. 2006. Simulation with system dynamics and fuzzy reasoning of a tax policy to reduce CO2 emissions in the residential sector. *European Journal of Operational Research. EJOR* **185**(3): 1285–1299.

Kwakkel JH, Walker WE, Marchau VAWJ. 2010. Classifying and communicating uncertainties in model-based policy analysis. *International Journal of Technology, Policy and Management* **10**(4): 299–315.

Kwakkel JH, Pruyt E. 2013a. Using system dynamics for grand challenges: The ESDMA approach. *Systems Research & Behavioral Science.* doi: 10.1002/sres.2225.

Kwakkel JH, Auping WL, Pruyt E. 2013. Dynamic scenario discovery under deep uncertainty: The future of copper. *Technological Forecasting & Social Change* **80**(4): 789–800.

Kwakkel JH, Pruyt E. 2013b. Exploratory modeling and analysis, an approach for model-based foresight under deep uncertainty. *Technological Forecasting & Social Change* **80**(3): 419–431.

Lane DC. 1998. Can we have confidence in generic structures? *Journal of the Operational Research Society* **49**(9): 936–947.

Lane DC, Oliva R. 1998. The greater whole: towards a synthesis of system dynamics and soft systems methodology. *European Journal of Operational Research* **107**(1): 214–235.

Lempert RJ. 2002. A new decision science for complex systems. *Proceedings of the National Academy of Sciences of the United States of America* **99**(3): 7309–7313.

Lempert RJ, Groves DG, Popper SW, Bankes SC. 2006. A general, analytic method for generating robust strategies and narrative scenarios. *Management Science* **52**(4): 514–528.

Lempert RJ, Popper SW, Bankes SC. 2003. *Shaping the next one hundred years: New methods for quantitative, long-term policy analysis*. RAND report MR-1626, The RAND Pardee Center, Santa Monica, CA.

Lempert RJ, Schlesinger ME. 2000. Robust strategies for abating climate change. *Climatic Change* **45**(3–4): 387–401.

Logtens T, Pruyt E, Gijsbers G. 2012. Societal aging in the Netherlands: Exploratory system dynamics modeling and analysis. In *Proceedings of the 30th International Conference of the System Dynamics Society*. St.-Gallen, CH, System Dynamics Society.

Luna-Reyes LF, Andersen DL. 2003. Collecting and analyzing qualitative data for system dynamics: methods and models. *System Dynamics Review* **19**(4): 271–296.

Lyneis JM. 2000. System dynamics for market forecasting and structural analysis. *System Dynamics Review* **26**(1): 3–25.

Lyneis JM, Ford DN. 2007. System dynamics applied to project management: a survey, assessment, and directions for future research. *System Dynamics Review* **23**(2-3): 157–189.

McCray GE, Clark TD. 1999. Using system dynamics to anticipate the organizational impacts of outsourcing. *System Dynamics Review* **15**(4): 345–373.

Meadows DH. 1980. The Unavoidable A Priori. In Randers J. (ed.) *Elements of the System Dynamics Method*, Productivity Press, Cambridge MA, 23–57.

Meadows DH, Richardson J, Bruckmann G. 1982. *Groping in the Dark: The first decade of global modelling*. Chichester: John Wiley and Sons.

Meadows DH, Robinson JM. 1985. *The Electronic Oracle. Computer Models and Social Decisions.* John Wiley & Sons, Chichester.

Miller J. 1998. Active nonlinear tests (ANTs) of complex simulation models. *Management Science* **44**: 820–830.

Morecroft JDW, Lane DC, Viita PS. 1991. Modeling growth strategy in a biotechnology startup firm. *System Dynamics Review* **7**(2): 93–116.

Morgan MG, Henrion M. 1990. *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis.* Cambridge University Press, Cambridge.

Moxnes E. 2005. Policy sensitivity analysis: simple versus complex fishery models. *System Dynamics Review* **21**(2): 123–145.

Ng TS, Sy CL, Lee LH. 2012. Robust parameter design for system dynamics models: a formal approach based on goal-seeking behavior. *System Dynamics Review* **28**(3): 230–254.

Oreskes N, Shrader-Frechette K, Belitz K. 1994. Verification, Validation, and Confirmation of Numerical Models in the Earth Sciences. *Science* **263**(5147): 641–647.

Pannell D. 1997. Sensitivity analysis of normative economic models: Theoretical framework and practical strategies. *Agricultural Economics* **16**: 139–152.

Peterson D, Eberlein R. 1994. Reality check - A bridge between systems thinking and system dynamics. *System Dynamics Review* **10**(2-3): 159–174.

Pruyt E. 2006. What is system dynamics? A paradigmatic inquiry. In *Proceedings of the 24th Conference of the System Dynamics Society*, Nijmegen. System Dynamics Society.

Pruyt E. 2007. Dealing with uncertainties? Combining system dynamics with multiple criteria decision analysis or with exploratory modelling. In *Proceedings of the 25th International Conference of the System Dynamics Society*, Boston, MA. System Dynamics Society.

Pruyt E. 2009. The Dutch soft drugs debate: A qualitative system dynamics analysis. In *Proceedings of the 27th International Conference of the System Dynamics Society*, Albuquerque, USA. International System Dynamics Society.

Pruyt E, Kwakkel JH. 2012. A bright future for system dynamics: From art to computational science and more. In *Proceedings of the 30th International Conference of the System Dynamics Society*. St.-Gallen, CH, System Dynamics Society.

Pruyt E, Kwakkel JH, Yucel G, Hamarat C. 2011. Energy Transitions towards Sustainability: A Staged Exploration of Complexity and Deep Uncertainty. In *Proceedings of the 19th International Conference of the System Dynamics Society*. Washington DC, System Dynamics Society.

Pruyt E, Kwakkel JH, Hamarat C. 2013. Doing more with models: Illustration of a system dynamics approach for exploring deeply uncertain issues, analyzing models, and designing adaptive robust policies. In *Proceedings of the 31st International Conference of the System Dynamics Society*. Cambridge, MA, System Dynamics Society.

Rahmandad H, Sterman JD. 2008. Heterogeneity and network structure in the dynamics of diffusion: Comparing agent-based and differential equation models. *Management Science* **54**(5): 998–1014.

Rahmandad H, Sterman JD. 2012. Reporting guidelines for simulation-based research in social sciences. *System Dynamics Review* **28**(4): 396–411.

Rahn RJ. 1985. Aggregation in system dynamics. *System Dynamics Review* **1**(1): 111–122.

Randers J, Göluke U. 2007. Forecasting turning points in shipping freight rates: lessons from 30 years of practical effort. *System Dynamics Review* **23**(2-3): 253–284.

Repenning N. 2000. Drive out fear (unless you can drive it in): the role of agency and job security in process improvement efforts. *Management Science* **46**(11): 1385–1396.

Repenning N. 2002. A simulation-based approach to understanding the dynamics of innovation implementation. *Organization Science* **13**(2): 109–127.

Richardson G, Pugh AI. (1981). *Introduction to System Dynamics Modeling.* Productivity Press: Portland. Previously published by MIT Press.

Richardson GP. 2011. Reflections on the foundations of system dynamics. *System Dynamics Review* **27**(3): 219–243.

Rotmans J, de Vries B. 1997. *Perspectives on Global Change: the TARGETS approach.* Cambridge, UK: Cambridge University Press.

Sharp J. 1976. Sensitivity analysis methods for system dynamics models. In J. Randers and L. K. Ervik (Eds.), *Proceedings of the International Conference on System Dynamics*, Geilo, Norway.

Sterman JD. 1991. Managing a Nation: The Microcomputer Software Catalog, Chapter A Skeptic's Guide to Computer Models, pp. 209–229. Boulder, CO: Westview Press.

Sterman J. 1994. Learning in and about complex systems. *System Dynamics Review.* **10**(2-3): 291–330.

Sterman JD. 2000. *Business dynamics: systems thinking and modeling for a complex world.* Irwin/McGraw-Hill: Boston.

Sterman JD. 2002b. All models are wrong: reflections on becoming a systems scientist. *System Dynamics Review* **18**(4): 501–531.

Strohhecker J. 2005. Scenarios and simulations for planning Dresdner Bank's e-day. *System Dynamics Review* **21**(1): 5–32.

Swart J, Hearne JW. 1989. A mathematical model to analyze predation and competition problems in a sheep-farming region. *System Dynamics Review* **5**(1): 35–50

Tan B, Anderson EG, Dyer JS, Parker GG. 2010. Evaluating system dynamics models of risky projects using decision trees: alternative energy projects as an illustrative example. *System Dynamics Review* **26**(1): 1–17.

Tank-Nielsen C. 1976. Sensitivity analysis in system dynamics. In *Proceedings of the International Conference on System Dynamics*, Geilo, Norway.

Tank-Nielsen C. 1980. Elements of the System Dynamics Method, Chapter Sensitivity Analysis in System Dynamics, pp. 185204. MIT Press/Wright-Allen Series in System Dynamics. Cambridge, MA: The MIT Press.

Taylor TRB, Ford DN, Ford A. 2010. Improving model understanding using statistical screening. *System Dynamics Review* **26**(1): 73–87.

Tessem B, Davidsen P. 1994. Fuzzy system dynamics: An approach to vague and qualitative variables in simulation. *System Dynamics Review* **10**(1): 49–62.

Thompson KM, Duintjer Tebbens RJ. 2008. Using system dynamics to develop policies that matter: global management of poliomyelitis and beyond. *System Dynamics Review* **24**(4): 433–449.

van Asselt MBA. 2000. *Perspectives on uncertainty and risk: The PRIMA approach to decision support.* Kluwer Academic, Dordrecht.

Vennix JAM. 1999. Group model-building: tackling messy problems. *System Dynamics Review* **15**(4): 379–401.

Warren, K. 2005. Improving strategic management with the fundamental principles of system dynamics. *System Dynamics Review* **21**(4): 329–350.

Wolstenholme, E. 1999. Qualitative vs quantitative modelling: the evolving balance. *Journal of the Operational Research Society* **50**(4): 422–428.

Walker WE, Harremoës J, Rotmans JP, Van der Sluijs JP, van Asselt MBA, Janssen PHM, Krayer von Krauss MP. 2003. Defining uncertainty: a conceptual basis for uncertainty management in model-based decision support. *Integrated Assessment* **4**(1): 5–17.

Walker WE, Lempert RJ, Kwakkel JH. 2013 (forthcoming). Deep uncertainty. In Gass SI, Fu MC. (Eds.) *Encyclopedia of Operations Research and Management Science* (3rd ed.). Springer.

Walker WE, Marchau VAWJ, Kwakkel JH. 2013. Uncertainty in the framework of policy analysis. In Thissen WAH, Walker WE. (Eds.) *Public policy analysis: New developments.* Springer Science + Business Media, New York. 215-261.

System dynamics (SD) is an approach to understanding the nonlinear behaviour of complex systems over time using stocks, flows, internal feedback loops, table functions and time delays. System dynamics is a methodology and mathematical modeling technique to frame, understand, and discuss complex issues and problems. Originally developed in the 1950s to help corporate managers improve their understanding of industrial processes, SD is currently being used throughout the public and private sector for... linear systems with state delays, uncertainties, and disturbances. When the information about the delays is not known, the terms. containing the delays are treated as an additional disturbance.Â In other words, the unknown dynamics and the disturbances udÍ'tÍ' can be observed by the system states and the control signal. However, it cannot be used in the control law directly. The UDE technique adopts an estimation of this signal. Researcher seeks to tame 'ghost' of. uncertainty in complex dynamic systems. 7 November 2017. We're surrounded by dynamic systemsâ€"systems external disturbances or intrinsic variability that. demonstrating behavior changing through timeâ€"in affects the dynamic process." engineering, nature, civilization, even our personal. lives.Â uncertainty." preliminary results." Back to the bathtub example, forecasting a possible water overflow during a bath is made more difficult due to unstructured uncertainties such as un-modeled dynamics (drain clogs), external disturbances (cats), inherent variabilities of the dynamic processes (movements of random bathers), sensor noise (water level gauge isn't 100 percent accurate) and data transmission errors (the. Wi-Fi is down). CONCLUSIONS. The dynamics of the entanglement and uncertainty relation is examined by solving the. TDSE of the coupled harmonic oscillator system when the angular frequencies Ï‰j and cou-pling constant J are arbitrarily time-dependent and two oscillators are in ground states. initially. To show the dynamics pictorially we introduce two toy models and one realistic. quenched model. While the dynamics can be conjectured by simple consideration in the. toy models, the dynamics in the realistic quenched model is somewhat dierent from that. in the toy models.