Preface

A model should always be created for a purpose.

Jay W. Forrester, Urban Dynamics (1969), p. 113

System dynamics is a modeling approach used to construct simulation models of social systems, and these computerized models can then support policy analysis and decision making. This simulation method is based on calculus, and models of real-world dynamic processes are constructed using integral equations.

A key strength of system dynamics is that the simulation models provide an integrated view across organizational boundaries and functional areas, and so support a *joined-up thinking* approach to problem solving. System dynamics also provides a unique way of viewing social systems. This is known as the *feedback perspective,* where cause and effect between different system elements can be formally analyzed to help explain system behavior, and so generate insight into how to make better decisions. System dynamics has been successfully applied across a range of application areas, including complex and challenging domains such as project management, health care, manufacturing, epidemiology, and climate change.

The aim of this book was to provide readers with a practical understanding of system dynamics, so that they are in a position to design and implement simulation models in their chosen problem area. The book is structured into three thematic areas.

- *Foundations* (Chaps. 1–2). Chapter 1 provides an introduction to modeling and system dynamics. Foundational system dynamics concepts are presented, including simulation based on stocks, flows, and feedback. Models are solved using calculus, and the principles of numerical integration are presented. Chapter 2 is a primer in the open source R programming language and environment. R supports statistical computing and data analysis, and also has libraries for numerical integration. Important R concepts such as vectors, data frames, and functions are covered, and a system dynamics model is implemented in R.

- *Dynamic models of social systems* (Chaps. 3–5). Chapter 3 introduces a method for representing cause and effect equations in system dynamics. It then presents three different growth models in system dynamics, including s-shaped growth, an economic growth model, and a non-renewable resource growth and decline model. Chapter 4 introduces delays, which are features of social systems, and also the stock management heuristic for regulating important stock resources. A healthcare model combining three sectors, population, delivery, and general practitioner supply is specified, and this demonstrates how system dynamics can be applied to *joined-up* policy planning issues. Chapter 5 presents diffusion models for infectious disease transmission and control and includes the classic susceptible–infected–recovered (SIR) model. This is extended with a disaggregated model and highlights the power of R to simulate, using matrix manipulation, inter-cohort disease transmission dynamics.
- *Model testing and analysis* (Chaps. 6–7). Chapter 6 focuses on model testing and summarizes the system dynamics approach to validation. Practical methods for testing models are presented and implemented using R's unit test framework. Chapter 7 introduces a formal approach to feedback loop analysis. It presents a valuable parameter analysis method known as statistical screening, which uses a base set of sensitivity simulation runs to generate a data set that is analyzed using statistical methods. The results of this analysis then highlight those parameters that have the greatest influence on a variable's trajectory, which can enhance the overall policy design process and provide decision makers with more information on potential intervention strategies. This chapter also describes the important area of model calibration, where key parameters can be estimated in order to find the best fit of historical data to the underlying model structure.

System Dynamics and Calculus

System dynamics is grounded in calculus, which is the study of how things change over time. Calculus is described by Strogatz and Joffray (2009) as *perhaps the greatest idea that humanity has ever had*. Calculus allows us to communicate at the speed of light, build bridges across great divides, and take action to halt the spread of epidemics. Sterman (2000) observes that the study of calculus can be quite daunting, as the use of unfamiliar notation, and a focus on analytical solutions, can deter many people.

However, integration is an intuitive concept that can be understood without reference to formal mathematics, and system dynamics uses integration to model things that change over time. For example, system dynamics simulation models that generate projections for population levels in cities, prevalence values for infectious disease outbreaks, and inventory levels in global supply chains all use integration as the simulation method. In Chap. 1, the process of integration is summarized, with an initial look at *analytical* solutions, before focusing on *numerical* approaches, which are widely used in system dynamics simulation tools.

Related System Dynamics Texts

This book provides a complementary perspective to the range of system thinking and system dynamics textbooks, which include the work of Sterman (2000), Morecroft (2007), Warren (2008), Ford (1999), and Maani and Cavana (2007). This book's focus is on quantitative stock and flow models, and, similar to Meadows (2008), does not address the use of qualitative causal loop models. The motivation here is to focus on the set of core modeling concepts and constructs that can provide the necessary practical knowledge for readers to build system dynamics models.

Because of this, a number of areas covered by other texts, and by ongoing research in the *System Dynamics Review*[1] are not covered. These include model structures such as co-flows, bounded rationality, and supply line management; machine learning methods for analyzing system dynamics output, for example, techniques such as classification and clustering which can be used to explore the policy space (Kwakkel and Pruyt 2013); advanced analytical methods such as calibration, estimation, decision support, and optimization, which can support the model building process (Rahmandad et al. 2015); and formal model analysis using mathematical approaches such as eigenvalue and eigenvector analysis, which provide powerful formal methods to analyze the structure and behavior of system dynamics models (Duggan and Oliva 2013).

Related Complexity Work in Other Disciplines

In system dynamics, the definition of a complex system refers to a high-order, multiple-loop nonlinear feedback structure (Forrester 1969), and all social systems can be viewed from this perspective. The *order* is simply the number of stocks (or states) in the system, for example, Forrester's urban model is twentieth order. *Multiple-loop* reflects the presence of circular causal links between state variables, and the interaction among these loops can explain a complex system's behavior. It is important to acknowledge complementary computational methods for exploring and understanding complex systems. While system dynamics operates at an aggregate level that captures feedback, other methods, such as agent-based modeling, view a complex system from an individual perspective. Agents (e.g., individuals) are represented in a spatial network structure and make decisions based on

[1]http://onlinelibrary.wiley.com/journal/10.1002/(ISSN)1099-1727.

local information (Railsback and Grimm 2011). Epstein (2006) describes the classical agent-based experiment as follows:

> Situate an initial population of autonomous heterogeneous agents in a relevant spatial environment, allow them to interact according to simple local rules, and thereby generate—or "grow"—the macroscopic regularity from the bottom up.

This definition concisely summarizes the agent-based modeling perspective. By focusing on an autonomous agent (which is usually a model of a person or an organization), individual differences are captured and codified. For example, an agent-based model of infectious disease transmission would include a profile of different individuals (infants, young children, teenagers, adults, and elderly), their disease status (susceptible, infected, or recovered), a map of their contact network (family contacts, friendship links, and workplace connections), and a model of disease transmission based on the frequency of interactions between infected and susceptible people. From these interactions, an overall pattern of behavior emerges, and the outbreak of a disease can be traced, over time, through a causal chain of networked connections.

While a discussion of agent-based modeling is outside the scope of this text, there are parallels between system dynamics and agent-based modeling. Specifically, the disaggregated disease transmission model in Chap. 5, where the population is subdivided into age cohorts, has parallels with the agent-based perspective, and readers looking to bridge from system dynamics to agent-based modeling are encouraged to use the infectious disease case as an exemplar, and also consider other works that have explored similarities between the two methods, for example, the study by Rahmandad and Sterman (2008).

Why R?

Published system dynamics texts use the excellent set of available special-purpose modeling software to implement system dynamics models. In this text, an open source approach is used, and system dynamics models are implemented using R. R is a powerful programming language designed to analyze and interpret data, and it has an extensive set of open source libraries that can support decision analysis. This includes the **deSolve** library (Soetaert et al. 2010), which supports numerical integration using a range of numerical methods. There are three reasons for using R for system dynamics modeling:

- R provides a comprehensive set of statistical and optimization functions that can be used to analyze and calibrate simulation output. For example, in Chap. 7, the statistical screening method for system dynamics models (Ford and Flynn 2005) is implemented, as is a calibration method for data fitting. R also has a differential equation solver that can be used to implement system dynamics models.

- R has a powerful visualization library that can be used to present the behavior space of system dynamics models, and so present policy scenarios in a convincing manner to decision makers.
- R is a leading platform for data science methods such as regression and classification to support data analytics. By also supporting implementation of system dynamics models, it means that analysts can adopt multimethod approaches in addressing complex problems.

Model Catalog

One of the most enjoyable aspects of system dynamics modeling is that the method can be applied in a range of domains. Therefore, modelers are presented with opportunities to work across disciplines and interact with experts in a range of domains, on challenging policy problems. The models presented in this text illustrate the breadth of application of system dynamics and include the following:

- Epidemiology, with a focus on a contagious disease model in Chap. 5, and an interesting extension of this to a disaggregate form, based on a vectorized R implementation.
- Health systems design, which, in Chap. 4, provides a joined-up model comprising population demographics, a supply chain of general practitioners, and a demand-capacity model of general practitioner services to overall population.
- Economics and business, ranging from simple customer model in Chap. 1, and onto models of limits to growth, capital investment, and the impact of non-renewable resources on growth, all of which are covered in Chap. 3.

Intended Audience

This book can be used as a supporting text for courses in system dynamics, simulation, complexity, and mathematical modeling. Previous knowledge of basic calculus and an understanding of algebra would be an advantage, although in system dynamics, the stock and flow notation is intuitive and practical. The book also can be used as a reference for consultants and engineers who design and implement system dynamics models and plan to align their work with data science methods such as regression and classification. A full set of model and code examples, and lecture slides, is available online at https://github.com/JimDuggan.

Feedback

Comments, suggestions, and critiques are most welcome, including ideas for further examples that could be added to the online resource. Feedback can be emailed to jim.duggan@nuigalway.ie.

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