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DISCRETE-EVENT SIMULATION AND SYSTEM DYNAMICS FOR MANAGEMENT DECISION MAKING

Editors

Sally Brailsford

Leonid Churilov

Brian Dangerfield

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This edition first published 2014

Registered office
John Wiley &
Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

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Library of Congress Cataloging-in-Publication Data

Discrete-event simulation and system dynamics for management decision making / [edited by] Sally Brailsford, Leonid Churilov, Brian Dangerfield.
pages cm
Includes bibliographical references and index.
ISBN 978-1-118-34902-1 (hardback)
1. Discrete-time systems–Simulation methods. 2. System analysis. 3. Decision making.
4. Management science. I. Brailsford, Sally. II. Churilov, Leonid. III. Dangerfield, Brian Thornley.
T57.62.D495 2014
658.4'0352–dc23

2013047217

A catalogue record for this book is available from the British Library.

ISBN: 978-1-118-34902-1

Set in 10/12pt TimesLTStd-Roman by Thomson Digital, Noida, India.

1 2014

We dedicate this book to Ruth Davies, Emeritus Professor of Operational Research at the University of Warwick, a great academic and a great friend.

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Preface

The genesis of operational research (OR) in the Second World War was largely characterised by deterministic techniques with a nod to risk evaluations such as in establishing the optimum balance of merchant ships and naval protection vessels in Atlantic convoy sizes. But it was part of the promulgation of OR techniques in large nationalised industries in the late 1940s and early 1950s that simulation came to the fore. This was particularly evident in the British steel industry. The emerging power of digital computers helped enormously and, under the guidance of luminaries such as Keith Tocher, discrete-event simulation (DES) (and the three-phase system) emerged from what had previously been Monte Carlo simulation.

Later in the 1950s in the United States another luminary, Jay Forrester, was settling into a new role at MIT and he saw the possibilities of applying the ideas and concepts from control engineering to the simulation of economic and social systems. Like Tocher, he relied on the growing power of computers. In fact he had been closely involved on the hardware side even to the extent of holding a US patent for random-access magnetic core memory. Forrester launched the field of what was to be system dynamics (SD), then known as industrial dynamics, in a paper in the *Harvard Business Review* in 1958.

Two powerful intellects were responsible for setting in train two separate methodologies in the domain of management science (MS) that, over the subsequent decades, have come to be employed on an enormous variety of applications. But although the simulation landscape has been enriched by their respective capabilities (which were rendered all the more impressive by the advent of icon-based computing) there has been almost no significant attempt to set out their respective merits in a comparative sense, still less to illustrate how they may be used in concert. This book, we believe, is the first volume to address these issues, while also describing agent-based (AB) modelling, another methodology that has recently emerged.

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1

Introduction

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1.1 How this book came about

To begin at the end . . . the final chapter in this book, by Michael Pidd, contains both a backwards and a forwards look at system dynamics and discrete-event simulation. Historically, both modelling approaches originate from around the same time, the late 1950s and early 1960s. However, over the intervening decades they developed into separate scientific and practitioner communities, each with its own learned societies, academic journals and conferences. Discrete-event simulation (DES) has been a core subject on MSc programmes in operational research (OR) or management science (MS) from the 1970s onwards, and is a standard technique in the 'OR/MS toolkit'. For many operational researchers, 'simulation' is synonymous with DES, and indeed the aim of the UK OR Society's own *Journal of Simulation* (quoting directly from the journal's web site) is to provide 'a single source of accessible research and practice in the fast developing field of discrete-event simulation' (http://www.palgrave-journals.com/jos/index.html). However, this is not true of system dynamics (SD): the SD community was, and still is to some extent, distinct from the OR community. While there is obviously some overlap in membership, there are many members of the international SD Society who are not members of their national OR Society (and vice

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versa). SD was certainly not taught on the MSc in OR at the University of Southampton in the 1980s and 1990s.

In 2000, the Simulation Special Interest Group of the UK OR Society held a joint meeting with the UK Chapter of the SD Society, entitled ‘Never the Twain Shall Meet’. At this meeting David Lane presented a paper (Lane, 2000) in which he discussed the differences between SD and DES and posed the question about whether they were ‘chalk and cheese’ or were actually two sides of the same coin. This meeting led to the foundation of a new OR Society Special Interest Group called ‘SD+’ whose aim was to bring the SD and OR communities together. The ‘+’ in SD+ was broader than just DES: it included many other OR techniques and approaches with which SD could interface. The ‘Never the Twain’ meeting also led to a number of academic papers exploring the similarities and differences between DES and SD, including the well-known study by Robinson and Morecroft which forms Chapter 9 of this book. Indirectly, it led to this book itself!

In some application areas the use of SD has expanded rapidly since 2000, and healthcare – the specialist application field of all three editors of this book – is one such area. However, despite initiatives like SD+, it is still true to say even today that SD is less well known in the mainstream OR community than DES. The number of DES papers at the annual Winter Simulation Conference, the major US conference on simulation, always greatly exceeds the number of SD papers. The main aim of this book is to begin to address this disparity. The book provides an integrated overview of SD and DES, a detailed comparison of the two approaches from a variety of perspectives, and a practical guide to how both may be used, either separately or together.

1.2 The editors

As editors, we should declare our own personal interests. Having started out in the early 1990s as a dedicated user of DES, Sally Brailsford became interested in SD as a result of the ‘Never the Twain’ meeting, and joined David Lane in co-founding the SD+ group. Subsequently she became a zealous convert, using SD for several modelling studies. Like many other researchers, she was fascinated by the relationship between DES and SD, and in particular in the domain of healthcare (Brailsford and Hilton, 2001), but first used SD in practice in a project to model demand for emergency healthcare in Nottingham, England (Brailsford *et al.*, 2004) which is described in detail in Chapter 6.

Leonid Churilov has a firm belief that real management problems do not come cleanly separated by disciplinary lines and, as a result, can rarely be comprehensively addressed using a single given modelling method. This basic premise is the source of continuous motivation for his keen interest in combining and contrasting different OR/MS techniques for management decision support. His research, in particular, included combining DES and clustering/classification techniques for decision support in hospital emergency departments, the use of both DES and SD for process systems modelling, and the original value-focused process engineering methodology that integrates the approaches from both the decision sciences and business process modelling domains. His work on philosophical underpinnings of both DES and SD worldviews from the critical realist perspective is featured in Chapter 5.

Brian Dangerfield discovered SD (industrial dynamics as it then was) over 40 years ago after a period in an OR unit in industry. Working at the (then) University of Liverpool School of Business Studies, he was a researcher on a project looking at the role of stocks in the UK economy. Rather than take the obvious econometric route he realised that an understanding of the macro role that stocks played in the workings of the economy would be much enhanced if, instead, macro-economic models were SD simulation models. Variables representing stocks had to be divorced from the flows which changed them. He was impressed with the way (i) SD models were forged at the policy level, (ii) separated out resource flows from the information flows driving changes in those resources and (iii) were also able to embrace relevant 'soft' variables which, using another methodology, might be excluded altogether. In sum he concluded that, given his overall knowledge and real-world experience with OR (including traditional simulation techniques), the SD methodology was just about the most promising in the landscape of OR, and his subsequent research career has concentrated on its use and development.

1.3 Navigating the book

To our knowledge this book is unique – there is no similar coverage in one single volume. Books which cover both methodologies (e.g. Pidd's *Computer Simulation in Management Science*, 2009) merely split the page coverage – there is no attempt at integration, or a detailed comparison and description of how both approaches may be used in the same project. This book provides a seamless treatment of a variety of topics: theory, philosophy, detailed mechanics and practical implementation, all written by experts in the field. While some chapters are aimed at beginners, others are more advanced; the book also includes three software chapters which are very practical in nature.

The book is structured in seven unequal sections, three of which only contain one chapter. This Introduction forms the first section, and Pidd's concluding chapter the seventh. The second section, 'Primers', contains two chapters which provide a basic introduction to DES and SD respectively. These chapters are both written by experts with many years' experience of teaching and using each technique: Chapter 2 on DES (Stewart Robinson) and Chapter 3 on SD (Brian Dangerfield). The authors assume no prior knowledge of either technique, or an academic background in mathematics, statistics or OR. They are aimed at students and practitioners alike. The aim of both primers is to provide sufficient understanding to enable the average reader to get a basic grasp of the topic and be able to appreciate the subsequent chapters. The primers do not attempt to provide the breadth and depth of material offered in a typical MSc course in SD or DES, and they do not contain a great deal of technical detail. References are provided for anyone who does wish to delve deeper into the technicalities!

The third section also consists of a single chapter. By way of contrast with Chapters 2 and 3, the authors of Chapter 4 (Kathy Kotiadis and John Mingers) take a strongly academic stance. This chapter provides a theoretical background for much of the discussion in later chapters about combining different modelling paradigms. This chapter, which was originally published as a research article in the *Journal of the Operational Research Society*, discusses the combination of problem structuring methods with hard OR methodologies. Kotiadis and Mingers reflect on the barriers to such combinations that can be seen at the philosophical level – paradigm incommensurability – and cognitive level – type of personality and difficulty of switching paradigm. They then examine the combination of soft systems methodology and DES within a healthcare case study. They argue, by way of the practical application, that these problems are not insurmountable and that the result can be seen as the interplay of the soft and hard paradigms. The idea of yin and yang is proposed as a metaphor for this process.

The fourth section, 'Comparisons', is by far the largest and represents the heart of the book – its *raison d'être*. It contains five chapters, all of which consider contrasting aspects of DES and SD, ranging from methodological and philosophical comparisons using different lenses or frameworks, through to practical aspects and software implementations. In Chapter 5, Leonid Churilov, Kristian Rotaru and Andrew Flitman investigate how the critical realist philosophy of science facilitates explicit articulation of the fundamental philosophical assumptions underlying the SD and DES worldviews, using a practical illustration of simulating process systems. The ultimate aim is to achieve more effective use of simulation for intelligent thinking about, and management decision support in, process systems. The novelty and original contribution of this research is in applying the stratified ontology of critical realism, and the abductive mode of knowledge generation, to examine explicitly the philosophical bases of the DES and SD simulation worldviews. The outcomes of this research are targeted at both the manager, who is the contributor to, as well as the end user of, a simulation model of a real-world process system and, as such, could benefit from a clear understanding of how management knowledge is generated through the modelling process, and the management scientist who chooses to use simulation modelling to support management decision making in real-world process systems, and requires in-depth understanding of the scientific bases of the respective modelling methodologies to apply them in a truly scientific manner.

It is an oft-quoted cliché that if all you have is a hammer, then every problem is a nail. The aim of Chapter 6 is to discuss whether the choice of simulation methodology – DES or SD – is purely down to the personal preference and expertise of the modeller, or whether there are identifiable features of certain problems that make one approach intrinsically preferable to the other. Although from a methodological standpoint the overall comments are generic and applicable to any setting, the chapter has a bias towards healthcare applications as this is the area of domain expertise of the author, Sally Brailsford. A case study in emergency care is presented, where both DES and SD were used to tackle different aspects of the overall problem. The chapter concludes with some general guidelines to assist the modeller in making the choice of technique.

One commonly held stereotype is that SD naturally lends itself to problems where a group of people with potentially conflicting objectives need to be engaged, on an ongoing basis, in the process of developing and running a simulation model, whereas DES is more naturally suited to problems where there is an agreed objective and, after an initial meeting with the client, the modeller goes away, locks him- or herself in a darkened room and spends a month writing code, requesting data, running the model and obtaining results, which the modeller then presents to the client at the next meeting. This is clearly rather an absurd exaggeration, but like all stereotypes it is worth examining to see whether it contains a grain of truth. The use of DES and SD models in group model building projects, where a group of domain experts or other stakeholders come together to build a model together with a modelling expert, is examined in Chapter 7. Steffen Bayer, Timothy Bolt, Sally Brailsford and Maria Kapsali show how both SD and DES models have a social function and can act as an 'interface' between participants in a modelling project. An interface can be understood as a point of interaction which allows two systems to communicate across a boundary. In everyday use 'interface' is, however, also often used as relating to what affords and enables the process of communication across the boundary: interface as the means or mechanism that allows the boundary between subsystems to be permeable. The metaphor 'interface' highlights the potential of models (and of the modelling process) to support information transmission in the widest sense between the participants in a group modelling project but also across the boundary between the model and those engaging with the model. The aim of this chapter is to explore and illustrate how the metaphor of interface can shed light on the variety of social functions models can have, especially in a group modelling context.

The actual model building process is explored in further detail in the following chapter, which focuses less on the social aspects of model building and more on the technical aspects, providing a detailed comparison of DES and SD by analysing the thought processes of the modellers themselves. In Chapter 8 Antuela Tako and Stewart Robinson describe an empirical study which used verbal protocol analysis to study the modelling process followed by ten expert modellers, five using SD and five using DES. The participants were asked to build simulation models based on a case study and to think aloud while modelling. The generated verbal protocols are divided into seven modelling topics (problem structuring, conceptual modelling, data inputs, model coding, validation and verification, results and experimentation, and implementation) and are then analysed. Quantitative analysis of the verbal protocols shows that all modellers switch between modelling topics; however, DES modellers follow a more linear progression. They focus significantly more on model coding and verification and validation, whereas SD modellers focus on conceptual modelling. Observations are also made, revealing some interesting differences in the way the two groups of modellers tackle the case. This chapter contributes to the comparison of DES and SD modelling in management decision making by providing empirical evidence with regards to the model development process.

The 'Comparisons' section concludes with Chapter 9, a contribution from John Morecroft and Stewart Robinson. Morecroft (an expert in SD) and Robinson (an expert in DES) compare SD and DES through an examination of the way each method analyses the puzzling dynamics inherent in a fisheries system. They begin by recounting comparisons between SD and DES made by other authors over the past 20 years or so. They lament that none of these comparisons are offered by neutral parties – all have a main affiliation with either DES or SD.

Morecroft and Robinson start their own comparison by presenting data charts from two well-known fisheries. In one a serious drop in annual fish ‘landings’ recovered eventually, but in the other the new rate of substantially lower catches has continued for over 40 years. A series of experiments are then undertaken involving building dual models of a stylised fishery – one in SD and the other in DES. The authors compare, step by step, the two emerging models, the equation formulations and the resultant simulated behaviour. They begin with a ‘natural’ fishery where there is no human involvement and then progress to a harvested fishery where ships are involved and the fish are landed. Initially the harvested fishery is modelled in equilibrium but this assumption is ultimately relaxed – in the SD model by adding a nonlinearity and in the DES model by adding randomness. The SD model exhibits growth initially but ultimately the fishery collapses. Turning to the DES model, there is still a collapse but over a different timescale: the greater the spread of the normal distribution generating the randomness, the faster the eventual collapse. The authors conclude with a final experiment where the harvested fishery now includes endogenous investment in ships. The authors demonstrate that, in both models, the policies for deciding on ship investments are defective. In conclusion they express the paradigmatic differences between the two approaches by stating that DES illuminates interconnected randomness whereas SD illuminates deterministic complexity.

Underpinning the developments in both DES and SD modelling, the improvements in software functionality stand supreme. As Pidd describes in Chapter 15, probably until well into the 1980s both these methodologies were employed in a manner which today’s user would find almost unbelievable. Text-based interfaces were the norm and the mainframe-supported software inevitably involved significant delays in delivering (usually printed) output. Common in DES at the time were such packages as GPSS and ECSL; in SD, DYNAMO and DYSMAP. All this changed by the mid-1990s as icon-based software became the norm, deployed on a PC and, latterly, on powerful laptop computers. Now users could experience almost instantaneous output together with the ability to display animated dynamic visual representations of their systems in real time.

This volume would be deficient if it did not afford some space to the consideration of contemporary software offerings. Accordingly, in the fifth section three authors have been invited to write about the software systems with which they are associated. Two were selected as being examples of commonly used software products for the methodologies covered by this volume and which had been in existence for at least 10 years to date; the third is a relative newcomer. The purpose of this book is such that an excessively lengthy documentation of relevant current software would be counterproductive. There are certainly other available systems for both DES and SD simulation and there is no intention to imply that those described here are in any sense superior; they are purely representative. And, going forward from here, Pidd ponders on possible future software developments in Chapter 15.

A word about the inclusion of AnyLogic is necessary as its emergence is relatively recent. Developments in the two principal methodologies covered here (and those related to them) are continuing apace. However, agent-based modelling (ABM) has emerged as a viable alternative to DES or SD simulation. Its use is primarily for certain types of problem, such as where a high level of (network) interaction detail and granularity is desirable and is capable of being represented as a feedback system. ABM would not exist if it were not for the astonishing developments in computer power in recent years. The AnyLogic system claims to allow for coding a problem as a DES, SD or ABM model. Whether one would wish to replicate a problem system in this way is open to debate. Usually the purpose of the investigation will dictate the approach adopted in coding the model. However, the availability of software such as AnyLogic means that, in theory, one would not need to utilise any other software system in order to create a methodologically diverse variety of systems models and, furthermore, it is possible to combine any of the three methods when using this software.

In Chapter 10 Mark Elder introduces a popular DES software platform – SIMUL8. He begins by emphasising that the model can aid understanding for the client such that he or she can have the confidence to change the process being managed for the better. Even rudimentary models can generate insight and a high-level model can produce the spark which spurs further investigation using more detailed models. While the thrust of this centres upon SIMUL8's dynamic 'floor plan' capabilities, and the way that this on-screen animation hooks in the client group, some of Elder's ideas about the benefits derived from the contemporary modelling process, rather than the model itself, would apply equally to SD.

He continues by taking the reader through an example model using the SIMUL8 software, depicting the processes involved in manufacturing metal tables. Some data can be automatically inserted by the software, thereby speeding up model creation. The need for replicated runs (trials) is emphasised together with the concomitant statistical analysis of the data generated. Some attention is given to the importance of verification and validation of the model as well as how to optimise the resources in the model. Finally, he concludes by considering the future for DES software.

Lee Jones continues the discussion of software matters by describing the Vensim SD simulation platform in Chapter 11. He starts by recounting how complexity in the modern business and social environment might be conducive to the growing use of SD. But this has not happened (particularly in business) and he conjectures that at its heart the issue may be bound up with SD software. Tracing the development of SD software platforms since the text-based environments of the 1980s, he recounts how Vensim's functionality has been improved over the years and how software user forums can now dictate the direction of additions to software functionality.

The importance of model units checks is underlined through the story of how NASA's Mars Climate Orbiter was destroyed on entry to the Martian atmosphere, merely because of a mismatch between metric and imperial units in the software driving the craft's orbital trajectory. Jones further considers calibration of a model to past (and indeed future) data using Vensim's optimisation feature. Other developments mentioned include the 'Reality Check' facility, together with 'Story Telling', the often problematic phase of SD modelling where the reasons for model behaviour have to be effectively communicated to the client; reduced form model diagrams, causes trees and strip graphs can all be usefully deployed to this end. Sensitivity graphs and policy optimisations can require many thousands of repeated runs and modern SD software harnesses the raw computing power now available in order to provide features of this sort. The chapter concludes by recounting how innovations in technology are helping the enhanced exposure of SD models: from the promulgation of models running live over the Internet, to the Facebook interactive game about how best to develop our planet ('Game Change Rio'); and, for the immediate future, the possible utilisation of tablet computers and smart phones for model execution and presentation.

In the final chapter in the 'Software' section (Chapter 12) Andrei Borshchev provides an account of the relatively recent offering: AnyLogic. His underlying theme is to illustrate how this platform can be employed to mix three simulation modelling methodologies – DES, SD and ABM – within the same overall problem. By introducing the concept of the statechart, Borshchev instances seven theoretical occurrences of how agents, discrete elements and SD stocks and flows can interact. Going into much more of the model formulation details, he then describes three specific examples: a supply chain where the market is handled using SD concepts while the supply chain itself involves the discrete-event methodology; an epidemic model exploring a clinic's capacity to cope, where the combination here is ABM and DES; and finally a product life cycle and new product investment policy where the formulation involves a mix of ABM and SD. However, it would be wrong to imply that only combinations of two methodologies are possible: the AnyLogic platform can be employed to develop simulation models where all three co-exist.

The sixth section, which contains two chapters, focuses on models and applications and begins with a practical guide to using different levels or scales of modelling. Chapter 13, by Geoff McDonnell and Rosemarie Sadsad, is dedicated to various aspects of multiscale modelling in the context of public health and health services management. Simulation models of complex and multilevel organisational systems like healthcare are often abstracted at one level of interest. There are many challenges with developing simulation models of systems that span multiple organisational levels and physical scales. Several theoretical and conceptual frameworks for multilevel system analysis are analysed and an approach for developing multiscale and multi-method simulation models to aid management decisions is presented. Simulation models are used to illustrate how management actions, informed by patterns in stock levels, govern discrete events and entities, which, collectively, change the flow mechanism that controls stock levels. The proposed approach explicitly considers the role of context when designing and evaluating, in particular, public health actions. It extends current analytical and experimental methods and has the potential to encourage more collaborative and multidisciplinary effort towards effective public health management.

Chapter 14 focuses on applications of combined simulation approaches, and its objective is to demonstrate the use of hybrid modelling for management decision support. The chapter presents three separate case studies that are unified both by the common theme of using different modelling techniques in a hybrid manner and by the health- and social care context. The first case study, by Geoff McDonnell and Rosemarie Sadsad, combines the use of SD and ABM to better understand and control the spread of a specific drug-resistant pathogen in hospitals; the second case study, by Joe Viana, demonstrates how a hybrid SD and DES model can support clinical and management decision making in the context of sexual health services in Portsmouth, UK; while the third case study, by Shivam Desai, is dedicated to the investigation of a hybrid model that consists of an SD-inspired cell-based population model and a DES model, used to explore the performance of a contact centre for long-term care for people aged 65 and over.

The final chapter is Michael Pidd's personal view of the future – and of the past. Pidd is of course well known as the author of one of the best known and most widely used textbooks on simulation, first published in 1984 and now in its fifth edition (Pidd, 2009). In the 1980s, general OR textbooks tended to have about 10 chapters on mathematical programming, 10 chapters on other analytical techniques, and then a final chapter on the statistical aspects of Monte Carlo simulation, only to be used *when all else fails*. No wonder that Pidd's highly readable, practical and comprehensive book on simulation became a classic. Moreover, unusually for a simulation textbook, even the first edition contained a section on SD. It is hard to think of a more appropriate person to conclude this volume, which we hope will prove useful to academics and practitioners alike.

References

Brailsford, S.C. and Hilton, N.A. (2001) A comparison of discrete event simulation and system dynamics for modelling healthcare systems. Proceedings of ORAHS 2000, Glasgow, Scotland (ed. J. Riley), pp. 18–39.

Brailsford, S.C., Lattimer, V.A., Tarnaras, P. and Turnbull., J.A. (2004) Emergency and on-demand health care: modelling a large complex system. *Journal of the Operational Research Society*, **55**, 34–42.

Lane, D.C. (2000) You just don't understand me: modes of failure and success in the discourse between system dynamics and discrete event simulation. LSE OR Dept Working Paper LSEOR 00-34.

Pidd, M. (2009) *Computer Simulation in Management Science*, 5th edn, John Wiley & Sons, Ltd, Chichester.

2

Discrete-event simulation: A primer

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2.1 Introduction

Discrete-event simulation (DES) grew largely out of a desire to model manufacturing systems. Based upon the foundation of Monte Carlo methods, DES models were developed to improve the design and operation of manufacturing plants. Among the earliest examples is the work of K.D. Tocher who developed the General Simulation Program in the late 1950s at the United Steels Companies in the United Kingdom; see Hollocks (2008) for an excellent summary of these early developments.

Over the years DES has been applied to a much broader set of applications including health, service industries, transportation, warehousing, supply chains, defence, computer systems and business process management. Much of this work has focused on improving the design and operation of the systems under investigation, but there have also been examples of DES for aiding strategic decision making.

DES is seen as a, if not the, mainstream simulation approach in the field of operational research (OR). Indeed, many OR specialists simply refer to it as 'simulation', seemingly ignoring the potential to simulate using other approaches, including system dynamics. DES does imply a very specific approach to simulation from both a technical and a philosophical perspective. In this chapter we will explore both of these perspectives. To set a context, we first present an example of a DES

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