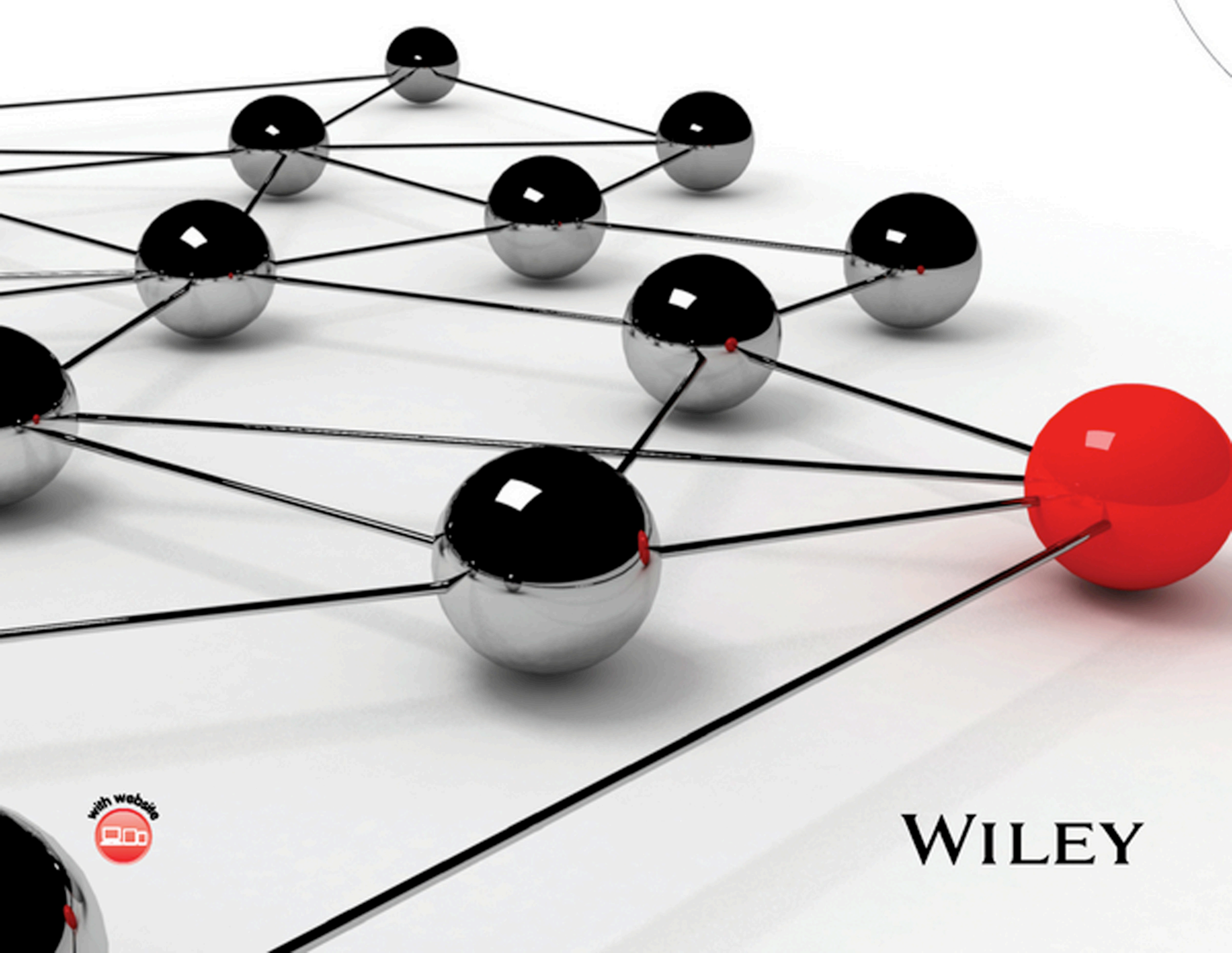
SECOND EDITION

SIMULATION MODELING AND ARENA®

MANUEL D. ROSSETTI



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Published by John Wiley & Sons, Inc., Hoboken, New Jersey
Published simultaneously in Canada

Library of Congress Cataloging-in-Publication Data:

Rossetti, Manuel D. (Manuel David), 1962- author.
Simulation modeling and Arena / Manuel D. Rossetti. – Second edition.
pages cm
Includes bibliographical references and index.
ISBN 978-1-118-60791-6 (cloth)
1. Computer simulation. 2. Arena (Computer file) I. Title.
QA76.9.C65R66 2015
003′.3–dc23

2015006381

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

2 2016

To all my students!

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PREFACE

Welcome to the second edition. Similar to the first edition, the book is intended as an introductory textbook for a first course in discrete-event simulation modeling and analysis for upper-level undergraduate students as well as entering graduate students. While the text is focused toward engineering students (primarily industrial engineering), it could also be utilized by advanced business majors, computer science majors, and other disciplines where simulation is practiced. Practitioners interested in learning simulation and Arena® could also use this book independently of a course.

The second edition has been significantly reorganized to allow more introductory material involving the application of spreadsheets to perform simulation. By including spreadsheet simulation, students are able to experience introductory concepts such as random number generation and sampling in a more familiar venue. Then, the concepts can be reinforced using Arena and discrete-event modeling. The book also introduces the use of the open-source statistical package, R, both for performing statistical testing and for fitting distributions. A significant number of additional exercises have been added to each chapter.

Manuel D. Rossetti
Fayetteville, AR

ACKNOWLEDGMENTS

I would like to thank my children, Joseph and Maria, who gave me their support and understanding, and my wife, Amy, who not only gave me support, but also helped in creating figures and diagrams and proofreading. Thank you so much!

M.D.R

INTRODUCTION

INTENDED AUDIENCE

Discrete-event simulation is an important tool for the modeling of complex system. It is used to represent manufacturing, transportation, and service systems in a computer program for the purpose of performing experiments. The representation of the system via a computer program enables the testing of engineering design changes without disruption to the system being modeled. Simulation modeling involves elements of system modeling, computer programming, probability and statistics, and engineering design. Because simulation modeling involves these individually challenging topics, the teaching and learning of simulation modeling can be difficult for both instructors and students. Instructors are faced with the task of presenting computer programming concepts, probability modeling, and statistical analysis all within the context of teaching how to model complex systems such as factories and supply chains. In addition, because of the complexity associated with simulation modeling, specialized computer languages are needed and thus must be taught to students for use during the model building process. This book is intended to help instructors with this daunting task.

Traditionally, there have been two primary types of simulation textbooks: (i) those that emphasize the theoretical (and mostly statistical) aspects of simulation and (ii) those that emphasize the simulation language or package. The intention of this book is to blend these two aspects of simulation textbooks together while adding and emphasizing the art of model building. Thus the book contains chapters on modeling and chapters that emphasize the statistical aspects of simulation. However, the coverage of statistical analysis is integrated with the modeling in such a way to emphasize the importance of both the topics. This book utilizes the Arena® simulation environment as the primary modeling tool for teaching simulation. Arena is one of the leading simulation modeling packages in the world and has a strong and active user base. While the book uses Arena as the primary modeling tool, the book is not intended to be a user's guide to Arena. Instead, Arena is used as the vehicle for explaining important simulation concepts.

I feel strongly that simulation is best learned by doing. The book is structured to enable and encourage students to get engaged in the material. The overall approach to presenting the material is based on a hands-on concept for student learning. The style of writing is informal, tutorial, and centered around examples that students can implement while reading the chapters. The book assumes a basic knowledge of probability and statistics and an introductory knowledge of computer programming. Even though these topics are assumed, the book provides integrated material that should refresh students on the basics of these topics. Thus, instructors who use this book should not have to formally cover this material and can be assured that students who read the book will be aware of these concepts within the context of simulation.

ORGANIZATION OF THE BOOK

Chapter 1 is an introduction to the field of simulation modeling and to modeling methodologies. After Chapter 1, the student should know what simulation is and be able to put the different types of simulation into context. It also describes an overall simulation methodology that has been proven useful both in the classroom and in practice.

Chapter 2 presents the theory and practice of generating random numbers and random variates from probability distributions. In addition, the student will know why random number generators and their control are essential for simulation modeling. The testing of pseudorandom numbers is also presented. After this chapter, the student should be aware of the methods used to generate and test pseudorandom number sequences. In addition, several methods of generating random variates are discussed (inverse transform, acceptance/rejection, convolution, and composition). These techniques are introduced without the added burden of computer methods.

The focus of Chapter 3 is on introducing Monte-Carlo methods within the context of a spreadsheet environment. Students will learn to put into practice the random number and random variate generation methods discussed in Chapter 2. In addition, the chapter presents materials on how to organize and perform basic simulation methods within a spreadsheet. The notions of sampling, sample size determination, and statistical inference are introduced.

Chapter 4 introduces Arena. First, Arena is used to perform simple Monte-Carlo simulation, similar to what was presented in Chapter 3. Chapter 4 also introduces the important concept of how a discrete-event clock ticks and sets the stage for process modeling using activity diagramming. A simple (but comprehensive) example of Arena is presented so that students will feel comfortable with the tool. Finally, debugging and how Arena processes events and entities are discussed.

Chapter 5 dives deeper into process-oriented modeling. The statistical aspects of simulation are downplayed within the chapter. The Basic Process template within Arena is thoroughly covered. Important concepts within process-oriented modeling (e.g., entities, attributes, activities, and state variables) are discussed within the context of a number of examples. In addition, a deeper understanding of Arena is developed including flow of control, input/output, variables, arrays, and debugging. After finishing Chapter 5, the student should be able to model interesting systems from a process viewpoint using Arena.

Chapter 6 emphasizes the role of randomness in simulation. After Chapter 6, the student should be able to model the input distributions required for simulation using tools such as R and the Arena Input Analyzer.

Building on the use of stochastic elements in simulation, Chapter 7 discusses the major methods by which simulation output analysis must account for randomness. The different types of statistical quantities (observation based versus time persistent) are defined and then statistical methods are introduced for their analysis. Specifically, the chapter covers the method of replication for finite-horizon simulations, the analysis of the initialization transient period, the method of replication–deletion, and the method of batch means. In addition, the use of simulation to make decisions between competing alternatives is presented.

Chapter 8 returns to model building by presenting models for important classic modeling situations in queuing and inventory theory. Both analytical and simulation approaches to modeling these systems are covered. For those instructors who work in a curriculum that has a separate course on these topics, this chapter presents an opportunity to concentrate on simulating these systems. The analytical material could easily be skipped without loss of continuity; however, often students learn the most about these systems through simulation. For those instructors where this material is not covered separately, background is presented on these topics to ensure that students can apply the basics of queuing theory and are aware of basic inventory models. Then, the basic models are extended so that students understand how simulation quickly becomes necessary when modeling more realistic situations.

Chapter 9 presents a thorough treatment of the entity transfer and material handling constructs within Arena. Students learn the fundamentals of resource-constrained transfers, free path transporters, conveyors, and fixed path transporters. The animation of models containing these elements is also emphasized.

Chapter 10 pulls together a number of miscellaneous topics that round out the use of Arena. In particular, the chapter covers activity-based costing and presents advanced aspects of modeling with resources (e.g., schedules and failure modeling). It also presents a few useful modules that were not previously covered (e.g., picking stations, generic stations, and picking up and dropping off entities). An introduction to using Visual Basic and Arena is also presented.

Finally, Chapter 11 presents a detailed case study using Arena. An IIE/Rockwell Software Arena Contest problem is solved in its entirety. This chapter ensures that students will be ready to solve such a problem if assigned as a project for the course. The chapter wraps up with some practical advice for performing simulation projects.

SPECIAL FEATURES

- Each chapter begins with specific learning objectives.
- Integrating the statistical aspects of simulation (e.g., output analysis) with the tool. More detailed discussions of the statistical aspects of simulation are presented than is found in many other simulation language-oriented textbooks.
- Studies have shown that activity-based learning is critical to student retention of material. The text is organized around the building of models with the intention

that students should be following along at the computer while working through the chapters. Instructors can perform the activities or organize computer laboratory exercises around the development of the models in the text.

- Special emphasis on the computer programming aspects of simulation: Students who take a course based on this text will be expected to have had at least one entry-level computer programming course; however, even with this background, most students are woefully ill-prepared to use computers to solve problems. The theory-based textbooks do not cover this material and the simulation package textbooks attempt to downplay the programming aspects of their environment so that the modeling environment appears attractive to noncomputer-oriented users. This book is intended to enable students to understand the inner workings of the simulation environment and thus demystify the black box. The language elements of the simulation environment are compared to standard computer language elements so that students can make the appropriate analogies to already studied material. Detailed presentation of pseudo-code enhances the understanding of the programming constructs.
- While Arena is the modeling tool, the conceptual modeling process presented in the text is based on language-independent methods including but not limited to rich picturing, elementary flowcharting, activity diagramming, and pseudo-code development. The emphasis is placed on developing a specification for a model that could be implemented in any simulation language environment.
- Coverage of classic stochastic models from operations research: One chapter is dedicated to queuing and inventory models. In many curricula, if the analytical models are presented, they will be taught in a different course. In my opinion, the simulation of classic models along with their analytical treatment can provide for deeper student learning on these topics. In addition, the presentation of these classic models both analytically and through simulation provides simple systems on which to build the teaching of complex more practical extensions.
- Comprehensive examples, exercises, questions, and problem sets developed from the authors' teaching, research, and industrial experiences.
- Students can download the Arena software directly from www.arenasimulation.com. Chapter illustrations and files (e.g., Arena and Microsoft® Office Excel®) are available from the course site. A comprehensive set of presentation slides are also available for students and instructors to use within the classroom. Finally, solutions for many of the exercises are available to instructors.

COURSE SYLLABUS SUGGESTION

Early versions of the manuscript for this textbook were used for multiple semesters in my course at the University of Arkansas. The course that I teach is to junior/senior-level undergraduate industrial engineering students. In addition, graduate students who have never had a course in simulation take the course. Graduate students are given extra homework assignments and are tested over some of the more theoretical aspects presented in the text (e.g., acceptance/rejection). I am able to cover most parts of Chapters Chapter 1–9 within a typical 16-week semester offering. A typical topic outline is as follows assuming 80-minute lecture periods.

#Lectures	Topic	Readings
1	Introduction	Chapter 1
2	Random number generation	Chapter 2
2	Random variate generation	Chapter 2
2	Spreadsheet Simulation	Chapter 3
2	Introduction to Arena	Chapter 4
4	Basic Process Modeling	Chapter 5
2	Input modeling	Chapter 6
2	Finite-horizon simulation	Chapter 7
3	Infinite-horizon simulation	Chapter 7
1	Comparing alternatives	Chapter 7
4	Queuing models	Chapter 8
5	Entity transfer and material handling constructs	Chapter 9
30		

I use three examinations and a project within the course. Examination 1 covers Chapters Chapter 1–3. Examination 2 covers Chapters Chapter 4–6. Examination 3 tests over Chapters Chapter 7–9. I do not formally test the students on the material in Chapters Chapter 10 and Chapter 11 since they will be using all previously learned material and components when performing their final project. Students are assigned homework throughout the semester and quizzed on the homework via online questions. In addition, to formal lectures, my course has a computer-based laboratory component that meets 1 day each week. During this time, the students are required to work on computer-based assignments that are based on the examples in the textbook.

ABOUT THE AUTHOR

Dr. Manuel D. Rossetti grew up in Canton, Ohio. He received his PhD and MSIE degrees in Industrial and Systems Engineering from The Ohio State University and his BSIE degree from the University of Cincinnati. He is a registered professional engineer in the State of Arkansas.

Dr. Rossetti joined the Industrial Engineering Faculty at the University of Arkansas in August 1999. He was awarded tenure and promoted to Associated Professor in August 2003 and promoted to Full Professor in August 2010. Dr. Rossetti was also appointed Associate Department Head for the Department of Industrial Engineering in August 2010. Dr. Rossetti currently serves as the Director for the Center for Excellence in Logistics and Distribution, a National Science Foundation Industry/University Cooperative Research Center.

His research interests include the design, analysis, and optimization of manufacturing, health care, logistics, and transportation systems using stochastic modeling, computer simulation, and mathematical modeling techniques. Dr. Rossetti has published over 85 journal and conference articles in the areas of transportation, manufacturing, health care, and simulation, and he has obtained over $4 million dollars in research funding. His research sponsors have included the Pine Bluff Arsenal, The Arkansas Science and Technology Authority, the Defense Logistics Agency, the Naval Systems Supply Command, the Air Force Research Laboratory, Wal-Mart Stores Inc., the Transportation Research Board, US Department of Transportation, and the National Science Foundation.

Dr. Rossetti was selected as a Lilly Teaching Fellow funded by the Lilly Endowment in 1997/1998 and won a UA Baum Teaching Enhancement Grant in 2002. Dr. Rossetti has won the UA Industrial Engineering Outstanding Teaching Award in 2002, 2008, and 2011. He has also been voted as the best IE teacher by IE students in 2007 and 2009. Dr. Rossetti received the John L. Imhoff Outstanding Teacher Award in 2011–2012 for the College of Engineering and the Charles and Nadine Baum Teaching Award for the University of Arkansas in 2013, the highest teaching honor bestowed at the university. In 2013, Dr. Rossetti was elected into the University of Arkansas' Teaching Academy.

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SIMULATION MODELING

LEARNING OBJECTIVES

- To be able to describe what computer simulation is.
- To be able to discuss why simulation is an important analysis tool.
- To be able to list and describe the various types of computer simulations.
- To be able to describe a simulation methodology.

1.1 SIMULATION MODELING

In this book, you will learn how to model systems within a computer environment in order to analyze system design configurations. The models that you will build and exercise are called simulation models. When developing a simulation model, the modeler attempts to represent the system in such a way that the representation assumes or mimics the pertinent outward qualities of the system. This representation is called a simulation model. When you execute the simulation model, you are performing a simulation. In other words, simulation is an instantiation of the act of simulating. A simulation is often the next best thing to observing the real system. If you have confidence in your simulation, you can use it to infer how the real system will operate. You can then use your inference to understand and improve the system's performance.

In general, simulations can take on many forms. Almost everyone is familiar with the board game Life™. In this game, the players imitate life by going to college, getting a job, getting married, etc. and finally retiring. This board game is a simulation of life. As another

Simulation Modeling and Arena®, Second Edition. Manuel D. Rossetti.

example, the military performs war game exercises which are simulations of battlefield conditions. Both of these simulations involve a physical representation of the thing being simulated. The board game, the rules, and the players represent the simulation model. The battlefield, the rules of engagement, and the combatants are also physical representations. No wishful thinking will make the simulations that you develop in this book real. This is the first rule to remember about simulation. A simulation is only a model (representation) of the real thing. You can make your simulations as realistic as time and technology allows, but they are not the real thing. As you would never confuse a toy airplane with a real airplane, you should never confuse a simulation of a system with the real system. You may laugh at this analogy, but as you apply simulation to the real world, you will see analysts who forget this rule. Don't be one.

All the previous examples involved a physical representation or model (real things simulating other real things). In this book, you will develop computer models that simulate real systems. Ravindran et al. [1987] defined computer simulation as "A numerical technique for conducting experiments on a digital computer which involves logical and mathematical relationships that interact to describe the behavior of a system over time." Computer simulations provide an extra layer of abstraction from reality that allows fuller control of the progression of and the interaction with the simulation. In addition, even though computer simulations are one step removed from reality, they are often capable of providing constructs which cannot be incorporated into physical simulations. For example, an airplane flight simulator can have emergency conditions for which it would be too dangerous or costly to provide in a physical-based simulation training scenario. This representational power of computer modeling is one of the main reasons why computer simulation is used.

1.2 WHY SIMULATE?

Imagine trying to analyze the following situation. Patients arrive at an emergency room. The arrival of the patients to the emergency department occurs randomly and may vary with the day of the week and even the hour of the day. The hospital has a triage station, where the arriving patient's condition is monitored. If the patient's condition warrants immediate attention, the patient is expedited to an emergency room bed to be attended by a doctor and a nurse. In this case, the patient's admitting information may be obtained from a relative. If the patient does not require immediate attention, the patient goes through the admitting process, where the patient's information is obtained. The patient is then directed to the waiting room, to wait for allocation to a room, a doctor, and a nurse. The doctors and nurses within the emergency department must monitor the health of the patients by performing tests and diagnosing the patient's symptoms. This occurs on a periodic basis. As the patient receives care, the patient may be moved to and require other facilities [magnetic resonance imaging (MRI), X-ray, etc.]. Eventually, the patient is either discharged after receiving care or admitted to the main hospital. The hospital is interested in conducting a study of the emergency department in order to improve the care of the patients while better utilizing the available resources. To investigate this situation, you might need to understand the behavior of certain measures of performance:

- The average number of patients who are waiting.
- The average waiting time of the patients and their average total time in the emergency department.

- The average number of rooms required per hour.
- The average utilization of the doctors and nurses (and other equipment).

Because of the importance of emergency department operations, the hospital has historical records available on the operation of the department through its patient tracking system. With these records, you might be able to estimate the current performance of the emergency department. Despite the availability of this information, when conducting a study of the emergency department, you might want to propose changes to how the department will operate (e.g., staffing levels) in the future. Thus, you are faced with trying to predict the future behavior of the system and its performance when making changes to the system. In this situation, you cannot realistically experiment with the actual system without possibly endangering the lives or care of the patients. Thus, it would be better to model the system and test the effect of changes on the model. If the model has acceptable fidelity, then you can infer how the changes will affect the real system. This is where simulation techniques can be utilized.

If you are familiar with operations research and industrial engineering techniques, you may be thinking that the emergency department can be analyzed by using queuing models. Later chapters of this book will present more about queuing models; however, for the present situation, the application of queuing models will most likely be inadequate due to the complex policies for allocating nurses, doctors, and beds to the patients. In addition, the dynamic nature of this system (the non-stationary arrivals, changing staffing levels, etc.) cannot be well modeled with current analytical queuing models. Queuing models might be used to analyze portions of the system, but a total analysis of the dynamic behavior of the entire system is beyond the capability of these types of models. But, a total analysis of the system is not beyond simulation modeling.

A key advantage of simulation modeling is that it has the capability of modeling the entire system and its complex interrelationships. The representational power of simulation provides the flexible modeling that is required for capturing complex processes. As a result, all the important interactions among the different components of the system can be accounted for within the model. The modeling of these interactions is inherent in simulation modeling because simulation imitates the behavior of the real system (as closely as necessary). The prediction of the future behavior of the system is then achieved by monitoring the behavior of different modeling scenarios as a function of simulated time. Real-world systems are often too complex for analytical models and often too expensive to experiment with directly. Simulation models allow the modeling of this complexity and enable low cost experimentation to make inferences about how the actual system might behave.

1.3 TYPES OF COMPUTER SIMULATION

The main purpose of a simulation model is to allow observations about a particular system to be collected as a function of time. So far the word *system* has been used in much of the discussion, without formally discussing what a system is. According to Blanchard and Fabrycky [1990], a system is a set of interrelated components working together toward a common objective. The standard for systems engineering provides a deeper definition:

> "A system is a composite of people, products, and processes that provide a capability to satisfy stated needs. A complete system includes the facilities, equipment (hardware and software), materials, services, data, skilled personnel, and techniques required to achieve, provide, and sustain system effectiveness." Air Force Systems Command (1991)

Figure 1.1 illustrates the fact that a system is embedded within an environment and that typically a system requires inputs and produces output using internal components. How you model a particular system will depend on the intended use of the model and how you perceive the system. The modeler's view of the system colors how they conceptualize it. For example, for the emergency room situation, "What are the system boundaries? Should the ambulance dispatching and delivery process be modeled? Should the details of the operating room be modeled?" Clearly, the emergency room has these components, but your conceptualization of it as a system may or may not include these items, and thus, your decisions regarding how to conceptualize the system will drive the level of abstraction within your modeling. An important point to remember is that two perfectly logical and rational people can look at the same thing and conceptualize that thing as two entirely different systems based on their "Weltanschauung" or world view.

Because how you conceptualize a system drives your modeling, it is useful to discuss some general system classifications. Systems might be classified by whether or not they are man-made (e.g., manufacturing system) or whether they are natural (e.g., solar system). A system can be physical (e.g., an airport) or conceptual (e.g., a system of equations). If stochastic or random behavior is an important component of the system, then the system is said to be stochastic; if not, then it is considered deterministic. One of the more useful ways to look at a system is whether it changes with respect to time. If a system does not change significantly with respect to time, it is said to be static, else it is called dynamic. If a system is dynamic, you might want to consider how it evolves with respect to time. A dynamic system is said to be discrete if the state of the system changes at discrete points in time. A dynamic system is said to be continuous if the state of the system changes continuously with time. This dichotomy is purely a function of your level of abstraction. If conceptualizing

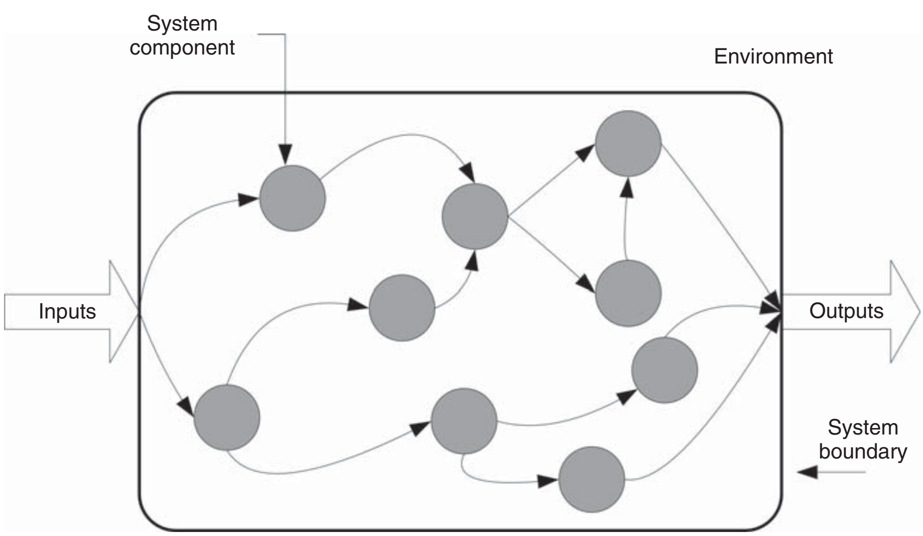

Figure 1.1 A conceptualization of a system.