Available online at www.sciencedirect.com
SciVerse ScienceDirect
journal homepage: www.elsevier.com/locate/jval

Modeling using Discrete Event Simulation: A Report of the ISPOR-SMDM Modeling Good Research Practices Task Force-4

Jonathan Karnon, PhD[1,], James Stahl, MDCM, MPH[2], Alan Brennan, PhD[3], J. Jaime Caro, MDCM[4], Javier Mar, MD[5], Jörgen Möller, MSC[6], on Behalf of the ISPOR-SMDM Modeling Good Research Practices Task Force*

[1]*School of Population Health and Clinical Practice, University of Adelaide, Adelaide, SA, Australia;* [2]*MGH Institute for Technology Assessment and Harvard Medical School, Boston, MA, USA;* [3]*University of Sheffield, Sheffield, England, UK;* [4]*United BioSource Corporation and Faculty of Medicine, McGill University, Montreal, QC, Canada;* [5]*Clinical Management Unit, Hospital Alto Deba, Mondragon, Spain;* [6]*United BioSource Corporation, Eslov, Sweden*

A B S T R A C T

Discrete event simulation (DES) is a form of computer-based modeling that provides an intuitive and flexible approach to representing complex systems. It has been used in a wide range of health care applications. Most early applications involved analyses of systems with constrained resources, where the general aim was to improve the organization of delivered services. More recently, DES has increasingly been applied to evaluate specific technologies in the context of health technology assessment. The aim of this article was to provide consensus-based guidelines on the application of DES in a health care setting, covering the range of issues to which DES can be applied. The article works through the different stages of the modeling process: structural development, parameter estimation, model implementation, model analysis, and representation and reporting. For each stage, a brief description is provided, followed by consideration of issues that are of particular relevance to the application of DES in a health care setting. Each section contains a number of best practice recommendations that were iterated among the authors, as well as among the wider modeling task force.

Keywords: discrete event simulation, best practices, modeling, methods.

Background to The Task Force

A new Good Research Practices in Modeling Task Force was approved by the ISPOR Board of Directors in 2010, and the Society for Medical Decision Making was invited to join the effort. The Task Force cochairs and members are expert developers and experienced model users from academia, industry, and government, with representation from many countries. Several teleconferences and hosted information sessions during scientific meetings of the Societies culminated in an in-person meeting of the Task Force as a whole, held in Boston in March 2011. Draft recommendations were discussed and subsequently edited and circulated to the Task Force members in the form of a survey where each one was asked to agree or disagree with each recommendation, and if the latter, to provide the reasons. Each group received the results of the survey and endeavored to address all issues. The final drafts of the seven articles were available on the ISPOR and Society for Medical Decision Making Web sites for general comment. A second group of experts was invited to formally review the articles. The comments received were addressed, and the final version of each article was prepared. (A copy of the original draft article, as well as the reviewer comments and author responses, is available at the ISPOR Web site: http://www.ispor.org/workpaper/Modeling-Using-Discrete-Event-Simulation.asp.) A summary of these articles was presented at a plenary session at the ISPOR 16th Annual International Meeting in Baltimore, MD, in May 2011, and again at the 33rd Annual Meeting of the Society for Medical Decision Making in Chicago, IL, in October 2011. These articles are jointly published in the Societies' respective journals, *Value in Health* and *Medical Decision Making*. This article summarizes the value of discrete event simulation (DES) to inform health care decisions and presents guidance on best practices in the application of DES. Other articles in this series [1–6] describe best practices for conceptualizing models, building and applying other types of models, addressing uncertainty, and ensuring transparency and validity. Examples are cited throughout, without implying endorsement or preeminence of the articles referenced.

* *Address correspondence to:* Jonathan Karnon, School of Population Health and Clinical Practice, University of Adelaide, Level 7, 178 North Terrace, Adelaide, SA 5005, Australia.
E-mail: jonathan.karnon@adelaide.edu.au.

1098-3015/$36.00 – see front matter Copyright © 2012, International Society for Pharmacoeconomics and Outcomes Research (ISPOR). Published by Elsevier Inc.
http://dx.doi.org/10.1016/j.jval.2012.04.013

Introduction

DES is a flexible modeling method characterized by the ability to represent complex behavior within, and interactions between individuals, populations, and their environments [7]. In health care, this means that events occurring to an individual and how that individual interacts with others, the health care system, and the general environment can be modeled simultaneously. The term "discrete" refers to the fact that DES moves forward in time at discrete intervals (i.e., the model jumps from the time of one event to the time of the next) and that the events are discrete (mutually exclusive). These factors give DES the flexibility and efficiency to be used over a very wide range of problems.

DES was developed in the 1960s in industrial engineering and operations research to help analyze and improve industrial and business processes. Applications in health care have increased over the last 40 years [8] and include biologic models [9,10], process redesign and optimization [11–13], geographic allocation of resources [14,15], trial design [16,17], and policy evaluation [18–20].

All DES represent an environment or a system, which may be a specific location (e.g., a hospital) or more generally, a particular disease in a defined population (e.g., persons with cardiovascular disease in Australia). A strategy is an alternative policy or configuration of the system, where the purpose of the model is to compare strategies to identify the one that best meets the decision-maker's criteria.

The core concepts of DES are entities, attributes, events, resources, queues, and time.

Entities are objects that have attributes, experience events, consume resources, and enter queues, over time. In health care models, they are typically patients, but they can be other people (e.g., caregivers) or items such as organs, or even signals (e.g., an e-mail) that can interact with other entities or the system itself. Entities can be created at the start or whenever it is appropriate to the problem (e.g., when a new patient arrives at a clinic, or develops a disease). The time of relevance to an entity may be a subset of the simulation time (i.e., individual entities can enter and leave a model between model start and end times).

Attributes are features specific to each entity that allow it to carry information (e.g., age, sex, race, health status, past events, quality of life, and accumulated costs). These values may be used to determine how an entity responds to a given set of circumstances (e.g., timing and type of past events may influence the likelihood and timing of subsequent events). Attribute values may be modified at any time during the simulation, may be aggregated with those of other entities, or analyzed further outside the simulation (e.g., to estimate mean cost and effect).

Events are broadly defined as things that can happen to an entity or the environment. An event can be the occurrence of clinical conditions such as onset of a condition (e.g., stroke), an adverse drug reaction, or progression of a disease to a new stage; resource use (e.g., admission to hospital); clinical decision (e.g., change in dose); or even experiences outside of health care (e.g., failure to show up at work). Events can occur, and recur, in any logical sequence.

A *resource* is an object that provides a service to an entity. This may require time. DES represents resource availability at relevant points in time (e.g., a clinic with three doctors is more likely to see a patient sooner than a one-doctor clinic). In representing resources, DES can capture spatial factors, such as the number of available consulting rooms or distance between a ward and an operating theatre (informing times to and from theatre).

If a resource is "occupied" when an entity needs it, then that entity must wait, forming a queue. Queues can have a maximum capacity, and alternative approaches to calling entities from queues can be defined: first-in-first-out (e.g., a typical waiting room queue); last-in-first-out, where entities get picked from the back of the queue; or based on some priority (such as emergency room triage).

A fundamental component of DES is time itself. An explicit simulation clock (initiated at the start of the model run) keeps track of time. Referencing this clock makes it possible to track interim periods (e.g., hospital length of stay, time spent with symptoms, and survival). The discrete handling of time means that the model can efficiently advance to the next event time, without wasting effort in unnecessary interim computations (e.g., a patient might have nothing happening for 2 years and then a myocardial infarction occurs, with ambulance, treatment, stroke, and other events occurring within minutes).

Other important concepts include interaction, which occurs whenever an entity competes with another over a resource, and emergent behavior, which is behavior that is characteristic of the system as a whole, such as spontaneous overcrowding in emergency rooms because elective surgeries are scheduled only once a week.

DES can be used to address a wide range of questions [21,22]. It allows for very flexible time management, events can occur anytime, without restricting occurrences to fixed time intervals [23]. DES is a particularly good choice when patients are subject to multiple or competing risks because its treatment of time allows for the optimal use of data describing the time to each event. Although this can be approximated in state transition models by using very short cycle lengths, this can lead to increased running times because the model has to check whether each event has occurred during every model cycle. DES is also a good choice when many patient characteristics must be taken into account, particularly if they change over time; when what happens next depends on what happened before; when the effects of decisions made along the way (rather than only at the start) are of interest; and whenever health care or disease processes involve a series of associated events (e.g., myocardial infarct to resuscitation to percutaneous coronary intervention (PCI) stenting to stroke).

There are two categories of DES applications in health care: non–constrained-resource [24–26] and constrained-resource models [27,28]. Non–constrained-resource models—although unusual in other fields that use DES—are required in our field to accord with the common structural assumption made in most health economic models today: that all required resources are available as needed, with no capacity limitations. In contrast, constrained-resource models incorporate these capacity limitations explicitly. They represent indirect interactions between individuals, generally involving multiple entities (e.g., patients) competing for access to resources (e.g., for clinic appointments or donor organs) and waiting in queues. Patients' demand for particular resources and their priority status in a queue may be influenced by their attributes. For such scenarios—the very problems for which it was developed—DES is clearly an appropriate choice.

DES can also be used to model more complex, direct interactions between individuals (e.g., transmission of disease). This "agent-based modeling [29,30]"—an extension of DES—provides more detailed representation of interactions between agents. An agent is an entity with embedded logic that determines how it responds to circumstances (e.g., will intimate interaction be accepted).

The remainder of this article covers design and structuring, estimation and specification of inputs, implementation, running and analyzing, and representation and reporting of DES models.

Structure and Design

DES design starts by defining the system to be represented and relevant events that can occur. Events need not be restricted to those that change an entity's health status; they can represent events that alter the likelihood of other outcomes (e.g., reperfu-