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Combining discrete-event simulation and system dynamics in a healthcare setting: A composite model for Chlamydia infection

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ABSTRACT

This paper presents a composite model in which two simulation approaches, discrete-event simulation (DES) and system dynamics (SD), are used together to address a major healthcare problem, the sexually transmitted infection Chlamydia. The paper continues an on-going discussion in the literature about the potential benefits of linking DES and SD. Previous researchers have argued that DES and SD are complementary approaches and many real-world problems would benefit from combining both methods. In this paper, a DES model of the hospital outpatient clinic which treats Chlamydia patients is combined with an SD model of the infection process in the community. These two models were developed in commercial software and linked in an automated fashion via an Excel interface. To our knowledge this is the first time such a composite model has been used in a healthcare setting. The model shows how the prevalence of Chlamydia at a community level affects (and is affected by) operational level decisions made in the hospital outpatient department. We discuss the additional benefits provided by the composite model over and above the benefits gained from the two individual models.

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1. Introduction

The potential benefits of combining discrete-event simulation (DES) and system dynamics (SD) have been discussed in the simulation literature for over a decade (Brailsford, Churilov, & Liew, 2003), prompted by an increasing realisation that many real-life problems cannot be divided neatly into the two opposing categories of *strategic* or *operational*, but may exhibit features of both. In many organisations, strategic decisions can rapidly affect day-to-day operations – and vice versa – due to organisational complexity and the speed of modern communications. Moreover, it is often difficult to draw clearly-defined boundaries round any part of a large system and study the resulting subsystem in isolation. This is particularly, although not uniquely, true in healthcare organisations, where "everything affects everything else". DES is a classical operational technique, designed for optimisation of system performance at a very detailed level and widely used since the 1950s. Although SD originated around the same time (Forrester, 1961) for many years it was not really part of the mainstream OR armoury. However, during the 1990s new OR techniques such as Strategic Options Development and Analysis (Eden, 1989) were developed and successfully used for strategic decision-making (Dyson & O'Brien, 1998). These approaches paved the way for system dynamics (SD) to become a more widely accepted part of the OR toolkit. SD is a more strategic tool, typically used at a much higher level, for understanding overall system behaviour.

Many researchers have considered the question of which approach should be used and when (Brailsford & Hilton, 2001; Brailsford et al., 2003; Morecroft & Robinson, 2006). More broadly, taxonomies have been developed to assess the advantages and disadvantages of various modelling approaches for specific problems in specific contexts, and provide guidance to modellers. Examples of such taxonomies in healthcare include Barton, Bryan, and Robinson (2004), Brennan, Chick, and Davies (2006); and Cooper, Brailsford, and Davies (2007). These taxonomies determine which methodology is best suited for a given problem, and work well if the problem fits neatly into their classification structures. Others have compared the differences in model-building approaches by users of DES and SD (Tako & Robinson, 2009).

DES is a stochastic modelling approach ideally suited to queuing network systems, where state changes occur at discrete points of time and individuals (entities) move stochastically through a system of queues and activities whose durations are sampled from

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probability distributions. It is a highly flexible approach in which almost anything can be coded; models can be incredibly detailed. Most DES software has a graphical interface which allows the user to see the system operating on the screen, almost like watching a movie. DES has the ability to capture *detail complexity*, the system behaviour that results from the possible combinations of many random processes, coupled with the system structure, leading to interconnection effects (Lorenz & Jost, 2006). The main limitations of DES are its inability to adequately capture the feedback dynamics associated with the holistic structure of a system, the very demanding data requirements to populate such models, and the need to perform multiple replications, leading to long runtimes.

The basic principle underlying system dynamics is that the structure of a system determines its behaviour over time (Forrester, 1961; Sterman, 2000). In other words, the way that the separate components of any system relate to and affect each other determines the emergent behaviour of the system as a whole. Such emergent behaviour can be counterintuitive, and it is only by analysis of the component subsystems that the reasons for this can be understood. Lorenz and Jost (2006) stated that SD models capture *dynamic complexity*, defined as the way variables can influence one another causing nonlinearities, delays and accumulative or draining relationships. SD has two distinct aspects, one qualitative and one quantitative. The qualitative aspect involves the construction of causal loop diagrams. Through discussions with problem owners and other stakeholders, the relationships between identified system elements are graphically depicted by a network of arcs and nodes, where the polarity of an arc indicates the direction of influence, positive or negative. The aim is to identify feedback loops, which can be of two kinds: balancing loops which retain a steady-state, or vicious circles leading to uncontrolled growth. The understanding and insights that this approach can bring are very useful. However the overall net effect of all the feedback loops in a complex system cannot be determined merely by inspecting the diagram. To do this it is necessary to quantify the variables, and this is not always straightforward if some variables (e.g. "happiness") are qualitative. Quantitative SD modelling requires the use of stock-flow diagrams. These models are best conceptualised as a system of tanks connected by pipes, around which water flows. The rate of flow is governed by taps or valves on the pipes. The "water" which flows around such a system is a continuous, homogeneous quantity. Mathematically, stock-flow SD models are a discretisation of a set of ordinary differential equations representing the rates of change of the level of each stock; these are solved numerically using a discrete time-step. Clearly, SD models are deterministic, and do not capture individual variability.

The "holy grail" (Brailsford, Desai, & Viana, 2010), and the research objective of this paper, would be to develop a methodology which combined the benefits and virtues of both DES and SD, allowing a truly holistic systems view yet at the same time capturing the essential detailed individual variability within parts of that system. The challenge is far greater than simply using continuous and discrete variables in the same model. Hybrid simulation executives designed to handle both continuous and discrete parameters have been available for many years. Most DES software packages can handle continuous variables and can therefore be adapted (albeit with some difficulty) to provide the underlying structures of SD models. Similarly, modern SD packages allow the user to sample from probability distributions. The aptly named AnyLogic (www.xjtek.com/AnyLogic) is a Java-based package in which it is possible to develop both DES and SD (and also agent-based) models. However although all these tools do produce models which contain both continuous and discrete parameters, they do not truly capture the spirit of SD and DES as understood by most users of these approaches and are only part of the story. A truly integrated approach would be advantageous because at a macro level, it could describe the movement of individual entities as a homogeneous flow, which would be fast and data-efficient, whereas at a micro level, where there were detailed interactions that affected the overall behaviour of the system, it would be possible to incorporate individual characteristics. The real challenge is therefore, not to develop software to handle continuous and discrete variables, but to develop both a conceptual philosophy and a practical methodology for combining SD and DES in a real context.

Combining different models in a hybrid framework to represent different parts of a larger system is of course not new. Frameworks for combining models have been proposed in many disciplines, including chemical engineering (Ingram, Cameron, & Hangos, 2004); construction (Alvanchi, Lee, & AbouRizk, 2011) and healthcare (Chahal & Eldabi, 2008). In addition to these discipline-specific frameworks, more generic frameworks are proposed by Shanthikumar and Sargent (1983), Chahal and Eldabi (2010), Morgan, Howick, and Belton (2011); and Swinerd and McNaught (2012). In each case the purpose was to deliver cost effective and computationally efficient solutions, incorporating those parts of the whole system which were required to gain greater insight.

Chahal and Eldabi (2008) identify three modes in which DES and SD can be combined. The simplest is the "hierarchical" mode in which two distinct models simply pass data from one to the other. The second mode is the "process environment" where there are still two distinct models, but the DES model actually sits inside the SD model and models a small section of the system, which then interacts cyclically with the wider SD environment. This is the approach used in the model presented in this paper. Finally, in the genuine "integrated" mode, there is one single hybrid model with no clear distinction between the discrete and continuous parts.

It has been suggested that healthcare systems in particular would benefit from a combined DES–SD approach (Brailsford et al., 2003). Bar-Yam (2006) argued that multi-scale modelling approaches are required to improve the effectiveness of the US health care and public health systems. Chahal and Eldabi's hybrid frameworks (2008, 2010) were devised with healthcare systems in mind. Morgan et al. (2011) modelled the radiotherapy delivery at a large Scottish hospital, utilising both DES and SD. The DES was used to understand and improve the operational capability of changing patient treatment regimes, and SD was used to understand the impact of wider system changes such as the impact of government targets and their interactions with R&D adoption. Ahmad, Ghani, Kamil, and Tahar (2012) used DES to model the detailed operations of an Emergency Department, and SD to model the wider hospital system. Brailsford et al. (2010) briefly presented two case studies representing the connections between the wider environment (depicted by an SD model) and a detailed subsystem (depicted by a DES model). One of these case studies was the Chlamydia model presented in much greater detail here.

This paper is structured as follows: Section 2 describes the problem context; Section 3 presents a DES model representing patient flows through the hospital clinic; Section 4 presents the SD Chlamydia transmission model primarily designed to investigate interventions; and Section 5 addresses the key research question of this paper, namely how and why the DES and SD models were combined. Finally, in Section 6 we reflect on the combined modelling approach and discuss the additional benefits provided by the composite model, over and above the benefits gained from the two individual models.

2. Problem context

Chlamydia trachomatis is the most common bacterial sexually transmitted infection (STI) in the world. About 70% of women and 50% of men are asymptomatic, meaning that infected people

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