System Dynamics Applications in Healthcare: 
A Literature Review

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Abstract

Healthcare simulation allows management to make decisions based on a solid framework. Continuous simulation is the foundation for systems dynamics, an approach to structure problems, understand those complex interactions within these problems and their changes over time. This paper reviews and resumes the state-of-the-art of system dynamics applications in healthcare. There are 74 publications related to system dynamics and healthcare that were identified in academic databases worldwide from 1999 to 2019. These articles were sorted by their characteristics, revealing that the applications of system dynamics have been broadly used in the healthcare to gain understanding about policy planning and public health decisions. The representation of patient behavior and technology advances, and the management of quality, staff and risk, are areas with potential application for systems dynamics in future research. The tendency to use continuous simulation in healthcare has been decreasing since 2014; however, the strength of hybrid simulation could exploit the innate power of the holistic view of system dynamics.

Keywords

1. Introduction

Healthcare is a large, complex and adaptive system that does not naturally lend itself to easy analysis, design, or even understanding (Koelling & Schwandt, 2005), because its dynamic components interact with each other creating a large complexity and several possible outputs (Atkinson et al., 2015). Effective and sustainable decision-making in healthcare requires tools that can address this complexity (Chahal & Eldabi, 2008). The critical nature of the system requires developing good representative models (Koelling & Schwandt, 2005) such as those used in computer simulations that are useful in healthcare because of its power and flexibility (Sally Brailsford, 2005).

Simulation is an analysis tool that uses the computer model of the system to estimate and evaluate the performance of models within a certain period in related operating conditions (Deryahanoglu & Kocaoglu, 2019). A simulation study begins with a real-world problem that needs to be solved, alleviated, or better understood. A conceptual model of the
problem is then developed and validated with domain experts. This model should be general, flexible, intuitive and simple (Fletcher & Worthington, 2009), since modelling health systems requires simplification of their complexity (Gunal, 2012). The conceptual model is then coded in computer software (Brailsford, et al. 2019). The resulting model is a replica of a real-world system on the computer and can be used to evaluate ‘what-if’ scenarios (Gunal, 2012) without causing unnecessary risk to patients admitted into the system (Wu, et al. 2019) or placing an unnecessary burden on the healthcare system (Alvarado, et al. 2017).

Continuous simulation is the basis for the application of system dynamics (SD), whose foundations were undoubtedly laid in the 1950s at MIT by Jay Forrester in his pioneering work on “industrial dynamics”, where the fundamental principle is that structure determines behavior (Brailsford, 2008). A healthcare system consists of many individual sub-parts that interact with each other, SD allows modeling of several sub-parts of these complex healthcare systems (Katsaliaki & Mustafee, 2011). Everything is connected to something else, and system dynamics models are more often associated with higher-level types of problems, especially considering the impact of policy and strategy decisions, (Koelling & Schwandt, 2005) rather than tracking individuals, optimization or point prediction because of the models' low accuracy (Brailsford & Hilton, 2001). SD concept involves systems thinking, including feedback, complexity and nonlinearity, and it is captured through causal loop diagrams (Koelling & Schwandt, 2005). A system dynamics model refers to the process of transforming a qualitative causal loop diagram into a stock-flow mathematical model (Atkinson et al., 2015), an interlocking a set of differential and algebraic equations developed from a broad spectrum of relevant measured and experiential data (Homer & Hirsch, 2006). Due to its capacity to define and explain system structures, feedback loops are the most widely used in both causal diagrams and models. SD is essentially a deterministic approach since there is usually no variability or stochastic aspect in a continuous simulation model. The model shows how variables change over time, allowing their behavior to be monitored and analyzed (Brailsford, 2008). Table 1 shows the characteristics of the system dynamics technique. Sometimes, simulation techniques are combined in a hybrid model, which is the efficient combination of various simulation modeling techniques such as SD, discrete event simulation (DES) and agent-based simulation (ABS) (Zhang, et al. 2019).

Table 1. Characteristics of continuous simulation

<table>
<thead>
<tr>
<th>SD characteristics according to Brailsford, (Sc Brailsford &amp; Hilton, 2001) Koelling (Koelling &amp; Schwandt, 2005) and Zhang (Zhang et al., 2019)</th>
<th>Strategic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scope:</td>
<td>Strategic</td>
</tr>
<tr>
<td>Purpose:</td>
<td>Policy and decision making, planning, gaining understanding, procurement logistic</td>
</tr>
<tr>
<td>Perspective:</td>
<td>Holistic, emphasis on dynamic complexity</td>
</tr>
<tr>
<td>Importance of variability:</td>
<td>Low</td>
</tr>
<tr>
<td>Importance of tracking individuals:</td>
<td>Low</td>
</tr>
<tr>
<td>Number of entities:</td>
<td>Large</td>
</tr>
<tr>
<td>Control:</td>
<td>Rates (flow)</td>
</tr>
<tr>
<td>Relative timescale:</td>
<td>Long</td>
</tr>
<tr>
<td>Resolution of models:</td>
<td>Homogenized entities, continuous policy pressures and emergent behavior</td>
</tr>
<tr>
<td>Data sources:</td>
<td>Broadly drawn</td>
</tr>
<tr>
<td>Lowest technical preparation:</td>
<td>Causal diagrams</td>
</tr>
<tr>
<td>Highest technical preparation:</td>
<td>Differential equations</td>
</tr>
<tr>
<td>Model elements:</td>
<td>Physical, tangible, judgmental and information links</td>
</tr>
<tr>
<td>Model outputs:</td>
<td>Understanding of structural source of behavior models, location of key performance indicators</td>
</tr>
<tr>
<td>Tools:</td>
<td>Vensim, AnyLogic, ExtendSim, STELLA/iThink</td>
</tr>
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</table>

Simulation approaches have been broadly used in healthcare, especially simulation, chiefly because of the advantages they have had over other techniques, such as their flexibility and their use of graphical interfaces to facilitate communication with, and comprehension by, healthcare professionals (Brailsford & Hilton, 2001). There are many reviews in the literature about simulation in healthcare, but there is no available a review that focuses on system dynamics applications in healthcare. With the motivation to prepare a systematic review, the focus of this paper are the applications of continuous simulation in healthcare, both pure and hybrid models that use system dynamics as one...
of the simulation techniques. By limiting the search strategy to research articles published in the last 20 years in academic databases, the objective of this study is to provide a literature review to find out what are the common approaches, tools, implementations and provenance of system dynamics applications in healthcare in order to identify directions for future research.

2. Methods

2.1 Search strategy

The databases IEEE, Scopus, ScienceDirect, Web of Science, Springer, ProQuest, Research Gate, Wolters Kluwer, Taylor & Francis, Wiley Online Library and PubMed Central were searched to retrieve articles focusing on system dynamics applications in healthcare between 1999 and 2019. Papers from these databases usually contain the most important journals and conferences of healthcare and system dynamics. The keywords formulated in the research are shown in Figure 1.

2.2 Paper inclusion criteria

The inclusion criteria focuses on studies that addressed the application of system dynamics in healthcare, including theoretical and practical approaches. As the focus was continuous simulation in healthcare, publications regarding discrete event and agent-based simulation were not included but, hybrid models were included if system dynamics was one of the techniques used for the study. Articles that do not fulfill the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) 2009 checklist were discarded. The searching and sorting processes and the number of papers selected were made in three levels, according to Figure 1. The focus area and scope of the review were decided after the screening process.

3. A summary and review of the system dynamics literature on healthcare

Following the retrieval of papers, the total number of essential SD applications in healthcare was 74. The search identified 60 pure system dynamics applications and 14 hybrid models. The publications of SD in healthcare reached its prime in the period 2010-2013, with 22 papers published. From the 74 total publications, 19 corresponded to conferences and 55 to journals (26% and 74% respectively). Considering only SD applications, 45 papers were published in the period 2004-2015, 8 articles were published in conferences and 52 in journals. For hybrid models, 12 papers were published in the last 8 years, and from the total 14, 11 papers were divulged in conferences and 3 in journals. The tendency of SD in healthcare growth until 2014, since then the number of papers published has been decreasing.
3.1 Implementation, techniques and tools

The representative papers identified in the search strategy were sorted to perform a qualitative analysis. The level of implementation was classified according to Brailsford et al. (2019) who proposed three types of simulation modeling:

- **Type A**: Papers that describe models built for specific applications, e.g. case studies (11% of the total papers in this review).
- **Type B**: Papers describing some kind of framework that could potentially be utilized by other modelers, illustrated with a case of study (80% of the identified papers).
- **Type C**: Papers that are purely theoretical, conceptual or methodological (9.5% of the papers).

More than three-fourths of the healthcare SD papers described a framework that could serve as the basis for other studies, while only around 10% of the papers were purely theoretical or specific applications. The system dynamics approach is used within health systems considering the general relationships and complexity in the long view, rather than operational or theoretical uses.

The system dynamics approach was used as a unique modeling technique in 81% of the papers identified. The combination of SD and DES represented 79% of the hybrid models. The combination of SD and ABS, as well as the SD, ABS and DES hybrid models are still unexplored in the healthcare area, and only three papers contained one of the combinations. Figure 2 shows the relationship between simulation technique and implementation.

![Figure 2. Type of paper by simulation technique and implementation](image)

The vast majority of the identified papers did not mention the tool/software utilized for the research (62%). Within the papers that mentioned the software utilized, Vensim is used in the 61% of the studies, STELLA/iThink 18%, AnyLogic 11%, ExtendSim 7.2% and Turbo Pascal 3.5%. The software Vensim is preferred for researches to use in the healthcare context for continuous simulation, while AnyLogic is the most used software for hybrid simulation.

3.2 Healthcare function

The main purpose of the application of simulation in healthcare is to obtain elements to make decisions and fulfill a requirement of a certain healthcare function. The identified papers were sorted following the classification of healthcare functions proposed by Brailsford, et al. (2009). Table 2 shows the eight types of healthcare functions, and Figure 3 shows the percentage distribution of the functions in the papers of the review.

Around 85% of the papers identified focus in finance, policy, governance, regulations, public health, planning and resource utilization (types 1, 2 and 4) in healthcare. Quality and staff management are the functions less studied in the publications identified, while continuous simulation for risk management in healthcare is still not explored. On the other hand, 72% of the papers are either type 1, 2 or 4 and describe a framework, while 74% of the papers only applied a system dynamics approach, which is mostly used in healthcare for finance, policy, governance, regulations, public health, planning or resource utilization and is illustrated with a case of study.
### Table 2. Healthcare functions

<table>
<thead>
<tr>
<th>Number</th>
<th>Function</th>
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<tbody>
<tr>
<td>Type 1</td>
<td>Finance, policy, governance, regulation</td>
</tr>
<tr>
<td>Type 2</td>
<td>Public health community, service planning</td>
</tr>
<tr>
<td>Type 3</td>
<td>Patient behavior/characteristics</td>
</tr>
<tr>
<td>Type 4</td>
<td>Planning, resource utilization</td>
</tr>
<tr>
<td>Type 5</td>
<td>Quality management</td>
</tr>
<tr>
<td>Type 6</td>
<td>Risk management</td>
</tr>
<tr>
<td>Type 7</td>
<td>Staff management</td>
</tr>
<tr>
<td>Type 8</td>
<td>Research</td>
</tr>
</tbody>
</table>

### 3.3 Countries and funding

Funding could play a critical role in the development and application of research. The SD in healthcare state-of-the-art review showed that only 32% of the papers identified mention that the study was funded. Contrary to what one might expect, funded research to specific applications represents only 8%, while research to develop frameworks represents 83%.

The United States is the country with more contribution to the literature, with 36%, followed by the United Kingdom with 26%, Germany with 7% and Poland with 5%. The rest of the countries contributed less than 5%. Publications conducted in Poland were all funded, around half of the publications from the U.S. had specific funding, and 40% of studies conducted in Germany were funded. From the countries with more contributions, hybrid research applications represent 100% of Poland's research, 60% of Germany's and 37% of UK publication, all papers coming from The United States were pure SD applications. There is an increasing tendency for hybrid simulation in Europe.

The software AnyLogic is used only in publications from Germany, ExtendSim only in research from Poland and STELLA/iThink is used in most of the papers published from the United Kingdom. The software Vensim is used broadly around the world.

### 4. Needs and research opportunities

System dynamics modeling is not an intervention, it is an analytical tool that can support policymakers to make more robust decisions in the presence of the significant uncertainty brought by complex problems. The modeling is the first step in a broader process that includes policy adoption, alignment of stakeholder actions, implementation and
maintenance, all of which are likely to influence whether the policy response has the expected impact. A proper evaluation of the effectiveness of SD modeling and its impact in healthcare functions is missing in the literature (Atkinson et al., 2015), and one of the reasons is that the number of publications has decreased after 2013. In addition to the obvious lack of evidence related to the efficiency of SD, there are 5 major areas of opportunity for continuous modeling research in healthcare that are described in the following sub-sections.

4.1 Hybrid models

Any model can capture limited range of factors that contribute to describe a system in real life, and these models include various simplifying assumptions (Bagust, Place, & Posnett, 1999). The modeler who chooses to use only one method is therefore faced with a dilemma: to model the whole problem using one single method, accepting that it makes invalid assumptions or oversimplifies some aspects (Brailsford et al., 2019). For instance, SD undeniably lacks the total flexibility of discrete event simulation, which can virtually use any probability distribution function, or empirical data, to model state dwelling times (Brailsford & Hilton, 2001).

Three different approaches have been broadly used for simulation: ABS, SD and DES. Every approach offers different capabilities and outputs, the proper combination of techniques would create robust models that represent in a better way the modeled system, resulting in a solid foundation for decision making.

4.2 Patient behavior and technology advances

The level of complexity of healthcare systems depends totally on human behavior. It is necessary to examine the physiological, psychological, and social aspects of patient care. Providers’ and patients’ behavior is directed by beliefs, attitudes, and expectations. The beliefs and attitudes are key aspects of the dynamic of healthcare functions (Paul, et al. 2010). The patient perspective is a relevant characteristic of patient care and the objective of every healthcare system. Simulation models in healthcare need to represent the patient perspective from a realistic view, human behavior.

Another missing aspect in healthcare models is the application of technology in health systems. The technology simplifies the labor to healthcare employees in a feedback loop which allows increasing efficiency as the interaction time with the technology rises. The inclusion of the combination of technology and patient behavior would affect directly in a positive way the prospective analysis and improvements of the healthcare functions.

4.3 Quality, staff and risk management

Critical aspects of management in healthcare are risk, quality and staff. The effectiveness of management in healthcare systems is the ability to respond to fluctuating demand and adjust framing policy, determining appropriate levels of service provision, and establishing realistic performance monitoring criteria (Bagust et al., 1999). Risks related to healthcare are always dynamic, and they are affected by situations of patients, human errors in treatment and even the states of medical devices (Li, et al. 2019).

System dynamics has not been the chosen approach for quality, staff and risk management in healthcare. The objective of management in service systems like healthcare is patient satisfaction. There are many factors affecting patient satisfaction like the behavior of healthcare providers, hospital factors, waiting times, level of experience of the physician, perception of care and cost of treatment (Deryahanoglu & Kocaoglu, 2019). The factors of patient satisfaction are correlated in a complex interaction, system dynamics approach needs to be implemented in models dealing with quality management, risks and staff in healthcare systems in order to understand the links that affect the drivers of the healthcare function, which are to reduce critical errors and increase patients safety.

4.4 Standardization: specific vs general models

One of the toughest tasks to the modeler is to define whether the model should be specific or generic. Beyond a certain point, the greater the level of detail, the greater the likelihood that a model will cease to be generic (Gunal, 2012). If an existing "generic" model represents a great level of detail of a function, the healthcare management will probably not accept the outputs of the model for their system, because, in a simple view, processes are different (Brailsford,
On the other hand, if a model does not represent a decent level of detail, the outputs will not be accepted for healthcare management due to the differences with the real system.

A great research opportunity is to define the guidelines for a checklist/framework which will lead to standardizing healthcare models which will allow defining the minimum aspects that generic models should have and determine the level of detail that differentiates a generic from a specific model. In addition, healthcare is driven by culture and local policies, to group generic models seems inevitable for the different areas of the world.

4.5 Avoid barriers to implementation

The ratio of models made to models implemented is low (Brailsford, 2005). The key challenges to apply models in healthcare are regulations, privacy and security, interdisciplinary collaboration, facility access (Alvarado et al., 2017). Data is another limitation since a simulation model is only as accurate as the data used to build it, therefore, the difficulty in capturing reliable data can lead to inaccurate simulation results (Paul et al., 2010). Moreover, a model’s input is also associated with the level of detail of the model. The more detailed the structure of the model is, the more inputs the model requires, and, if data are unavailable, some required details may be compromised (Gunal, 2012).

In addition to challenges, there are several barriers to implementation for simulation in healthcare, according to Brailsford (2005):

- **Culture**: The healthcare industry is characterized by constant change, upheaval and stress. Typically, management in healthcare is being replaced constantly, and many healthcare workers are resistant to yet more change, as they struggle just to cope with each day's workload. There is a physiological resistance to methods adopted from the manufacturing industry and a feeling that such models are trying to reduce human beings to widgets in a production line and thus are doomed to failure.
- **Cost**: Most simulation software is costly, and modeling and statistical expertise is very expensive. Despite the vast amount of data collected routinely in hospitals, it is rarely in a form suitable for modeling, so further money must be spent on data cleaning and analysis.
- **Data**: Healthcare data are notorious for poor quality, also it has some issues as the legal status of certain patient documentation.
- **Perverse incentives**: The high prices of consultancies have led to models made by academics. Academics need to publish in journals and need to demonstrate theoretical or methodological advances, leading to complex and sophisticated models, while the end-user needs a simple, easy to use model.

There is no a magic formula to avoid barriers to implementation, but models implemented have some common factors: complexity reduced to a level at which modeling objectives can be achieved (Gunal, 2012), at least one author worked at the institution concerned, models were prepared with timeliness, gained funding from the owner of the system, a detailed description of data collection (Brailsford, 2005), and models created to treat evolving regulations and policies in healthcare (Alvarado et al., 2017).

5. Conclusions

System dynamics uses continuous simulation to understand the dynamic complexity from a holistic perspective. After the searching in 11 academic databases and the characterized screening process, the studies examined in this review indicate a tendency to use system dynamics in healthcare to gain understanding about finance, regulations, public health decisions, service planning and resources utilization, with a framework usually illustrated with a case of study. A small proportion of the publications were funded, a factor to consider for understanding the reason why less than 15% of the system dynamics applications are made to specific areas or problems. The United States is the country that contributes the most to literature, which shows the efforts of the health management of the country to continuously improve the quality of the healthcare services. Vensim is the most used software for the studies.

The tendency to use systems dynamics in healthcare has been decreasing in the last five years, and some suggestions can be offered in order to gain credibility in the literature. Thus, models involving systems dynamics in healthcare need to consider elements as: 1) defeat the physiological barrier that healthcare management put against the implementation of simulation, showing that simulation is a tool to help people; and 2) models need to be simple and
easy to interact with the final user, considering a proper combination of practicality and level of detail, leaving out complex theoretical and conceptual methods from the models.

The system dynamics approach in healthcare has many unexplored ideas for future research, such as the standardization of generic models in healthcare that commonly address similar problems with the same technique, which in turn, cause confusion, duplicity of studies and delays in the literature. Healthcare models must consider the patient's perspective as well as the support that technology provides to health system agents, the advancement of technology for general processes and transactional operations is an essential element in the health sector today that simply cannot be ignored. Further, a hybrid approach is necessary to face the complexity and uncertainty of the health sector with a firm and consolidated decision making system. Given the characteristics of continuous simulation, combining systems dynamics with another approach in a hybrid model could exploit the innate power of the holistic view of system dynamics to manage healthcare systems in an innovative way.

References


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Appendix 1: Articles consulted for the review of literature


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**Biographies**

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