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Simulation Modelling in Healthcare: An Umbrella Review of Systematic Literature Reviews

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Abstract

BACKGROUND: Numerous studies examine simulation modelling in healthcare. These studies present a bewildering array of simulation techniques and applications, making it challenging to characterise the literature.
OBJECTIVE: The aim of this paper is to provides an overview of the level of activity of simulation modelling in healthcare and the key themes.
METHODS: Umbrella review of systematic literature reviews of simulation modelling in healthcare. Searches were conducted of academic databases (JSTOR, SCOPUS, PUBMED, IEEE, SAGE, ACM, Wiley Online Library, Science Direct) and grey literature sources, enhanced by citation searches. The articles were included if they performed a systematic review of simulation modelling techniques in health care. After quality assessment of all included articles, data was extracted on numbers of studies included in each review, types of applications, techniques used for simulation modelling, data sources and simulation software.
RESULTS: The search strategy yielded a total of 117 potential articles. Following sifting, 37 heterogeneous reviews were included. Most reviews achieved moderate quality rating on a modified AMSTAR checklist. All the review articles described the types of applications used for simulation modelling; 15 reviews described techniques used for simulation modelling; 3 reviews described data sources used for simulation modelling; and 6 reviews described software used for simulation modelling. The remaining reviews either did not report or did not provide enough detail for the data to be extracted.
CONCLUSION: Simulation modelling techniques have been used for a wide range of applications in healthcare, with a variety of software tools and data sources. The number of reviews published in the recent years suggest an increased interest for simulation modelling in healthcare. (263 words)

Keywords

Simulation modelling, health care, discrete event simulation, system dynamics, agent-based simulation

Key Points for Decision Makers

- This umbrella review provides a centralized repository of information for readers to understand the current state of the knowledge for the use of simulation modelling in healthcare.
- Simulation modelling techniques have been used to support a wide range of health care decision problems, and the number of reviews published recently suggest an increased interest in the use of these techniques.
- Readers can identify the systematic reviews that are best suited for their particular research questions, either based on problem type or simulation modelling technique.

1. Background

There is a large amount of literature on simulation modelling in health care and the number of studies has increased over the last twenty years. These studies present a bewildering array of simulation techniques and applications in healthcare, which may cause confusion among individuals who are new to this literature (e.g. policymakers, early career operational researchers and healthcare professionals). The substantial time and resources required to conduct a systematic review of this diffuse literature is unlikely to represent an optimal approach to sensitisation to this literature.

Umbrella approaches can be used to review and compile evidence from multiple systematic literature reviews into a sole review. The umbrella approach allows the reader to get an overview of the literature relevant to the topic at hand [1], rather than analysing every individual study that have been published on the topic of interest. For example, Mahdavi *et al.* [2] conducted a preliminary search of systematic review studies to assess the volume of relevant papers using generic models in healthcare. Secondly, this approach enables the reader to assess and consider different reviews efficiently when similar research questions need to be addressed [3]. Thus, we used the umbrella approach as it represents a powerful and appropriate tool for our review purpose.

In this review, our aim was to provide an overview of simulation modelling in healthcare and assess the quality of the reviewed studies. The next section presents the methods used for this review. Section 3 presents the results of the quality assessment and synthesis of the reviewed studies. This is then followed by the discussion and conclusion section.

2. Methods

2.1 Literature searches

A systematic literature search was conducted in academic databases (JSTOR, SCOPUS, PUBMED, IEEE, SAGE, ACM, Wiley Online Library, Science Direct) and other sources for grey literature (Google Scholar, "FreeFullPDF" site, winter simulation conference archive). Pearl growing techniques [4] were used to identify list of keywords related to simulation modelling in healthcare and to develop the search strategies. The searches focused on reviews that have been published between January 1990 to May 2017. These searches were also supplemented with manual searches of references from the included studies.

2.2 Study selection

Articles found using the search strategy, after removing duplicates, were screened at the title and abstract level by two reviewers (SS and PT). Full texts for the remaining articles were assessed in detail

and included if both reviewers found them relevant. Reviews were included if the article is considered a systematic review or systematic literature review; clearly presents the review purpose, the search strategy, and the inclusion criteria; if the article reviewed the applications of simulation modelling in healthcare; and if the article included a detailed description (e.g. at least a paragraph, figure, table or lists of references) of the applied simulation techniques and its application areas from individual studies. Studies were excluded if they were not literature reviews, not in healthcare, not in English or not a journal article.

2.3 Data extraction and quality assessment

A data extraction form was used to assess the following characteristics of the reviews: the total number of simulation studies assessed, range of years reviewed, types of healthcare applications, techniques used for simulation modelling, sources of input data and software tools used for simulation modelling.

We selected the AMSTAR (**a** **m**ea**s**urement **t**ool used to **a**ssess systematic **r**eviews) checklist from [5] which is widely recognised as a way of evaluating reviews [6]. The AMSTAR tool consists of 11 key questions that have adequate face and content validity to measure quality of systematic reviews effectively [6]. However no instrument currently exists to assess the quality of methodology reviews. This study therefore used AMSTAR as the basis to develop a method for evaluating the quality of reviews, while reinterpreting some of the questions in the context of simulation studies. Minor modifications were made with the aim of preserving the original intent of checklist items while making the tool applicable for assessing the quality of simulation reviews. The AMSTAR checklist with its additional purpose-specific prompts, to address issues specific to simulation modelling reviews, is presented in *Appendix 1.*

2.4 Analysis

The data extracted from the reviews was synthesised and the information gathered was discussed in detail to identify common themes. A quantitative, qualitative and narrative summary of the results from the systematic reviews was presented. The analysis also incorporated insights gathered during the full-text reading of the included reviews.

3. Results

3.1 Searches, sifting, data extraction categories and quality assessment

The search strategies to identify systematic literature reviews of simulation modelling in healthcare, developed using pearl growing techniques, are presented in *Appendix 2.* The search strategies yielded a total of 117 potential articles. After elimination of duplicates 105 articles remained. The first stage of screening (i.e. abstract and title level) conducted using the inclusion and exclusion criteria led to a total of 46 articles being excluded - 14 articles as they were not a systematic literature review, 9 articles for not being in healthcare and 23 articles for using a different definition of simulation (e.g. simulation techniques used for medical training, integration testing, comparative study). The second stage of screening included a detailed assessment (i.e. a full-text reading) of 59 articles, which resulted in 22 further articles being excluded - 10 articles as they were not a systematic literature review, 6 articles for not being in healthcare, 5 articles for using a different definition of simulation and 1 article is not a journal article (i.e. University of Twente discussion paper). The results from the two stage sifting process

are presented visually as a PRISMA (**P**referred **R**eporting **I**tems for **S**ystematic Reviews and **M**eta-**A**nalyses) diagram in *Figure 1.*

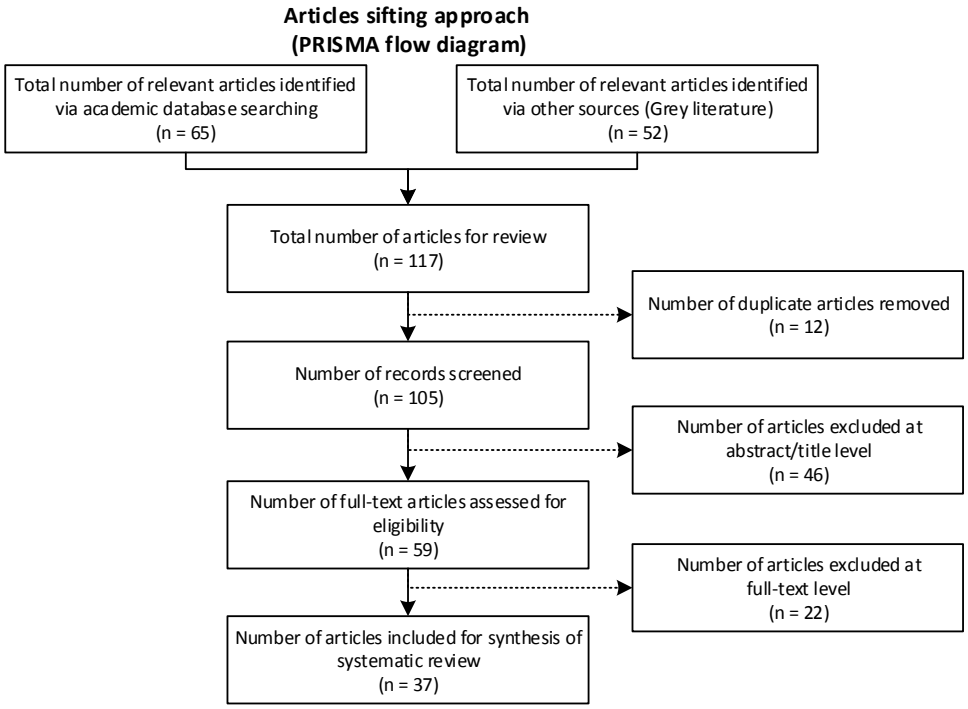

Figure 1: PRISMA diagram

The synthesis and the discussion in this paper relates to the 37 review articles included. Each review article was read carefully to absorb the detail provided. Key themes were then identified by examining the type of information presented on the simulation studies included within each review. Each of the review articles varied in terms of the type of information presented, as observed in Appendix 3. However, the categories of information that were included in most of the reviews were journal type, year of publication, country, objectives, methods, applications, tools, data used, outputs and critical appraisal of the studies.

The next steps were to choose the categories for data extraction and then extract the data from the reviews that included these categories. Among the categories that were identified above, journal type, year of publication and country were excluded from data extraction stage, as this was beyond the scope of the current paper. Furthermore, objectives, outputs and critical appraisal of the studies were also excluded from data extraction stage due to the qualitatitve nature of the information. The readers are encouraged to refer to Appendix 3 and the corresponding reviews for more detailed information on the categories excluded.

The four categories chosen and extracted from the reviews were the types of applications, techniques used for simulation modelling, data sources and simulation software used for modelling.

Furthermore, the full text of articles that met the inclusion criteria was subjected to quality assessment using the modified AMSTAR checklist and was allocated quality ratings of high, moderate or low. Out of the 37 included reviews, most of the reviews achieved a rating of moderate (30 review articles), while the rest exhibited high (3 review articles) or low (4 review articles) quality ratings. The four articles

which achieved low ratings were also included for data extraction and synthesis, as they offered valuable insights into simulation modelling in healthcare. The detail of the quality assessment results for all the included studies are presented in Appendix 4.

3.2 Overview of the reviews included

Table 1 provides a general overview of the 37 reviews, which includes the type of review, years covered, the number of studies identified and categories extracted in each review. There are a few key themes that can be identified from this high level overview of the reviews. Firstly, there is an increase in number of reviews being published with time. There are only 2 studies published prior to 2005, with 5 published in years 2005-2009 and 30 since 2010. This indicates that the level of activity and interest in simulation modelling for healthcare is increasing.

Table 1: The 37 reviews included

Review	Type of review	Years covered in search strategies	Number of studies reviewed	Reviews eligible for data extraction based on the four reviewed categories			
				Applications used for SM	Techniques used for SM	Data sources used for SM	Software used for SM
Klein *et al.* [7]	An annotated bibiliography and review of simulation modelling and healthcare decision making	1981-1992	93	✓			
Fone *et al.* [8]	A narrative systematic review of the use and value of computer simulation modelling in population health and healthcare delivery	1980-1999	182	✓			
White [9]	Survey of data resources for simulating patient flows in healthcare delivery systems	1997-2004	35	✓		✓	
Hoot *et al.* [10]	Review of emergency department crowding from the perspective of causes, effects and solutions	1977-2007	93	✓			
Sobolev *et al.* [11]	Review the use of computer simulation modelling of patient flow in surgical care	1957-2007	34	✓	✓		
Jack *et al.* [12]	Review of demand management, capacity management and performance in healthcare services	1986-2006	463	✓			
Brailsford *et al.* [13]	Review of operational research modelling approaches in healthcare	1952-2007	342	✓	✓		
Mielczarek *et al.* [14]	Survey of the main trends in the applications of simulation modelling in the healthcare	1999-2006	168	✓	✓		✓
Paul *et al.* [15]	Review of simulation studies investigating emergency department overcrowding from the fields of healthcare, systems engineering, operational research and computer science.	1970-2006	43	✓		✓	
Mustafee *et al.* [16]	Profiling literature in healthcare simulation	1970-2007	201	✓	✓		
Cardoen *et al.* [17]	Review of operational research in operating room planning and scheduling	1950-2009	247	✓	✓		
Katsaliaki *et al.* [18]	Review applications of simulation within the healthcare context	1970-2007	201	✓	✓		✓
Guerriero *et*	Survey of operational research in the management of the	1975-2010	48	✓			

al. [19]	operating theatre						
Günal *et al.* [20]	Review the use of discrete event simulation for performance modelling in healthcare	1965-2009	75	✓			
Van Sambeek *et al.* [21]	Review models for the design and control of patient flows within departments in a hospital process	1974-2006	68	✓			
Fakhimi *et al.* [22]	Review of operational research methods applied in the UK healthcare sector	1992-2011	70	✓	✓		✓
Hulshof *et al.* [23]	Review of operational research and management science methods in resource capacity planning and control in healthcare	1952-2012	462	✓			
Van Lent et al. [24]	Review relation between simulation and improvement in hospitals	1997-2008	89	✓			
Beliën *et al.* [25]	Review on inventory and supply chain management of blood products	1966-2010	98	✓			
Aboueljinane *et al.* [26]	Review use of simulation for the analysis and improvement of emergency medical service	1969-2013	31	✓			
Fakhimi *et al.* [27]	Review operations research within UK healthcare	2000-2012	142	✓	✓		
Timbie *et al.* [28]	Review of strategies to optimise the management and allocation of scarce resources during mass casualty events	1990-2011	74	✓			
Pomey *et al.* [29]	Review of understanding the determinants of wait time management success to help decision-makers and managers better manage wait times	1990-2011	47	✓			
Verbano *et al.*, 2013 [30]	Review the tools, practices and guidelines to improve quality and patient safety in healthcare	2004-2013	47	✓			
Lakshmi *et al.* [31]	Review application of queueing theory in healthcare	1952-2011	141	✓			
Mahdavi *et al.* [2]	Review generic operational models in healthcare service operation management	1990-2010	116	✓			
Kammoun *et al.* [32]	Review use of discrete event simulation in hospital supply chain management	2003-2013	33	✓			
Carey *et al.* [33]	Review of the application of systems science and systems thinking in public health	1990-2015	117	✓			
Atkinson *et al.* [34]	Review use of system dynamics modelling for health policy	1999-2013	6	✓	✓		
Baru *et al.* [35]	Review use of operation research and/or simulation models in hospital bed management	1998-2013	21	✓	✓		✓
Isern *et al.* [36]	Review applications of agents in the healthcare domain	2009-2014	97	✓	✓		
Gul *et al.* [37]	Review simulation applications of emergency department for normal and disaster conditions	1968-2013	106	✓	✓	✓	✓

Vieira *et al.* [38]	Review operation research methods for logistics optimisation in radiotheraphy	2000-2015	33	✓			
Mielczarek [39]	Review of the application of simulation methods applied in healthcare	1999-2012	232	✓	✓		
Palmer *et al.* [40]	Review of operational research methods for modelling patient flow and outcomes within community healthcare	1984-2016	53	✓			
Soh *et al.* [41]	Review the application of validated simulation models in hospital-wide surgical services	2002-2016	22	✓	✓		
Mohiuddin *et al.* [42]	Review simulation methods and their contributions for the analysis of patient flow within UK emergency departments	2000-2013	21	✓	✓		✓

Abbreviations: *SM, simulation modelling.*

Second column of table 1 highlights the diversity of topics that are considered within the reviews. Two broad classifications emerge – reviews of certain types of simulation modelling techniques and reviews of certain types of healthcare applications i.e. whilst some of the studies are broad reviews (i.e. reviews of studies that use *simulation modelling* in *healthcare)* some reviews are either limited to certain simulation modelling techniques (e.g. DES) or certain healthcare applications (e.g. emergency departments). For example, reviews by Günal *et al.* [20] and Kammoun *et al.* [32] look only at studies using DES; Atkinson *et al.* [34] look at SD; Lakshmi *et al*. [31] look at queueing models, while the rest of the reviews do not restrict by specific techniques i.e. they consider all simulation modelling techniques. On the other hand, as seen in *Table 1*, majority of the reviews solely focus on simulation studies related to healthcare operations and system design [2, 9-11, 13, 15, 17, 19, 21, 23, 24, 26, 29-32, 35, 38, 40-42] with the rest of 16 reviews [7, 8, 12, 14, 16, 18, 20, 22, 25, 27, 28, 33, 34, 36, 37, 39] assessing multiple types of applications.

The third and fourth columns of table 1 present the years covered and the number studies included in each review. As expected, the number of studies included depend upon the scope of the review and when it was conducted. For example, there are more studies included in broader reviews (i.e. reviews of *simulation modelling* in *healthcare*) than reviews that were limited to specific simulation modelling techniques or healthcare applications. Similarly, as the amount of literature is increasing each year, there are more studies included in reviews that were conducted later.

Columns 5-8 present the reviews eligible for data extraction based on the four chosen categories. All 37 reviews described category 1, the types of applications used for simulation modelling; 15 described category 2, techniques used for simulation modelling [11, 13, 14, 16, 17, 18, 22, 27, 34-37, 39, 41, 42]; 3 described category 3, data sources used for simulation modelling [9, 15, 37]; 6 described category 4, software used for simulation modelling [14, 18, 22, 35, 37, 42]. The remaining reviews either did not report these categories or did not provide enough detail for the data to be extracted.

3.3 Data extraction

3.3.1 Types of applications

To differentiate the heterogeneity of studies assessed within these articles identified in the umbrella review, the applications were classified into four major groups:

1. Healthcare operations and system design: use of simulation modelling for resource management or system design with the aim of optimising healthcare service flow (e.g. reducing queue or waiting time within healthcare department) or forecast resource demands (e.g. predicting the number of beds required to meet the expected patient demand).
2. Medical decision-making applications: use of simulation modelling to gain information regarding the implication of short term or long term effects of a particular program for effective decision making (e.g. using cost effectiveness analysis for selection of interventions or policy).
3. Infectious disease modelling: use of simulation modelling to predict the rate of spreading epidemics, assessing the economic consequences or estimating future resources required to treat the growing number of infected population (e.g. cost needed to manage influenza disease).
4. Miscellaneous studies: simulation studies used for mass casualty event planning (e.g. terrorist attacks) or a review (e.g. reviewing the development, improvement or comparison of simulation techniques as a feasibility study).

These classifications were identified by carefully reviewing the applications presented in the 16 included articles, and combining into groups that best fit all application areas. This decision was made by discussion and consensus of two reviewers (SS and PT).

As presented in *Table 1*, 21 of the reviews solely focus on simulation studies related to healthcare operations and system design [2, 9-11, 13, 15, 17, 19, 21, 23, 24, 26, 29-32, 35, 38, 40-42].

Table 2 presents the remaning 16 reviews which present multiple types of applications and the classification of the applications of simulation studies, within those articles [7, 8, 12, 14, 16, 18, 20, 22, 25, 27, 28, 33, 34, 36, 37, 39]. The numbers of simulation studies relating to the different application groups were identified and extracted from the sixteen reviews. It should be noted that the data included in the reviews by Mustafee *et al.* [16] and Katsaliaki *et al.* [18] was the same and hence presented only once in *Table 2*. As observed, most of the studies relate to healthcare operations and system design with medical decision making applications second, whilst infectious disease modelling and other miscellaneous studies make up the rest.

Table 2: Studies classified by healthcare applications

No.	Classifications of study	No. of studies identified														
		[7] (n= 93)	[8] (n= 182)	[12] (n= 463)	[14] (n= 168)	[16, 18] (n= 201)	[20] (n= 75)	[22] (n= 70)	[25] (n= 98)	[27] (n= 142)	[28] (n= 74)	[33] (n= 117)	[34] (n= 6)	[36] (n= 97)	[37] (n= 106)	[39] (n= 232)
1	Healthcare operations and system design	29	94	16	88	17	48	15	13	20	0	3	3	9	101	109
2	Medical decision-making applications	16	81	1	41	82	1	34	12	23	0	5	3	2	0	90
3	Infectious disease modelling	5	7	0	14	0	0	0	1	0	13	5	0	10	0	0
4	Miscellaneous studies	43	0	0	13	102	26	5	2	25	7	0	0	0	5	33
Total (X)		93	182	17	156	201	75	54	28	68	20	13	6	21	106	232

**n= Total number of studies reviewed; X= Total number of studies/results able to perform data/information extraction into categories via the reviewed articles*

3.3.2 Simulation Techniques used

Out of the 37 reviews identified, only 15 [11, 13, 14, 16-18, 22, 27, 34-37, 39, 41, 42] presented the details of the types of techniques used for simulation modelling among the studies identified in their reviews. *Table 3* presents the results of simulation techniques used in the studies identified within these fifteen reviews. DES is the most widely used technique with Monte Carlo simulation and system dynamics models also commonly used. Agent-based modelling techniques appear relatively rare but seem to be coming into usage more recently. It is apparent that hybrid modelling is new to this field and there has not been a significant amount of research conducted on it, with only one review reporting on hybrid models. Interestingly, only two reviews [11, 23] presented studies using the Markov model or the cohort simulation techniques. The possible reason is that these techniques are commonly combined (e.g. alongside discrete-event simulation or system dynamics techniques) and were not reviewed separately in other reviews.

Table 3: Articles presenting techniques used for simulation modelling

No.	Simulation techniques	No. of studies identified													
		[11] (n=34)	[13] (n=342)	[14] (n=168)	[16, 18] (n=201)	[17] (n=247)	[22] (n=70)	[27] (n=142)	[34] (n=6)	[35] (n=21)	[36] (n=97)	[37] (n=106)	[39] (n=232)	[41] (n=22)	[42] (n=21)
1	Discrete-event simulation (DES)	26	37	118	40	29	18	31	-	12	-	101	136	19	19
2	Monte-carlo simulation (MCRLO)	2	24	15	142	8	11	16	-	1	-	-	46	-	-
3	System-dynamics simulation (SD)	3	6	23	17	-	1	4	6	-	-	-	39	2	2
4	Agent-based simulation (ABM)	-	-	-	2	-	-	-	-	-	29	5	11	-	-
5	Hybrid simulation model (e.g. DES+SD)	-	-	-	-	-	-	-	-	-	-	-	-	1	-
6	Markov model	1	-	-	-	-	-	-	-	-	-	-	-	-	-
7	Cohort simulation (CS)	-	-	-	-	-	1	-	-	-	-	-	-	-	-
Total (X)		32	67	156	201	37	31	51	6	13	29	106	232	22	21

3.3.3 Data sources

Out of the 37 simulation articles identified in the umbrella review, only 3 articles [9, 15, 37] discussed the model data sources. *Table 4* presents the results of data sources used as inputs in the studies identified within these three articles. The data used for modelling ranged from primary data collection (e.g. hospital databases, observation and time studies), secondary data (e.g. literature, questionnaires) as well as expert opinion (e.g. interviews, workshops).

Table 4: Articles presenting source of input data used for simulation modelling

No.	Data source for simulation modelling	No. studies identified		
		[9] (n=35)	[15] (n=43)	[37] (n=106)
1	Hospital database	22	4	34
2	Observation and time study	6	2	28
3	Interview/Expert opinion	8	1	30
4	Medical record	2	1	11
5	Survey/Questionnaire	2	1	5
6	Logs	2	1	19
7	Case study/Literature	2	0	0
8	Payment record	0	1	1
9	Patient chart	0	1	0
10	Process modelling workshop	0	0	2
11	Data generator	0	0	1
Total (X)		44	12	131

3.3.4 Software used for simulation modelling

Only 6 articles [14, 18, 22, 35, 37, 42] discussed the software tools used for model development. *Table 5* presents the results of simulation tools used for modelling, split by techniques (DES, SD, MCRLO, ABM), in the studies identified within these six articles. A wide variety of software tools were used for simulation modelling but no clear recommendations were made about software within these reviews.

Table 5: Articles presenting tools used for simulation modelling

No.	Tools for simulation modelling	No. of studies identified					
		[14] (n=168)	[18] (n=201)	[22] (n=70)	[35] (n=21)	[37] (n=106)	[42] (n=21)
DES							
1	ARENA	28	6	1	1	33	2
2	Programming Language (Delphi, C++, Visual Basic (VB), SLAM, Bordland, PASCAL, GPSS/H, FORTRAN IV, SIMSCRIPT II.5, JAVA)	25	9	1	2	4	1
3	SIMUL8	5	3	2	0	10	10
4	MedModel (Promodel)	9	0	0	1	11	1
5	ExtendSim	3	1	0	0	5	0
6	Microsaint	4	0	5	2	2	2
7	Compound	4	0	0	0	0	0
8	Automod	0	2	0	0	1	0

9	SIGMA	0	2	1	0	0	0
10	Service (Promodel)	0	1	0	0	1	0
11	SIMAN	0	1	0	0	2	0
12	AnyLogic	0	0	1	0	1	0
13	Witness	0	0	0	1	1	0
14	Microsoft Excel	0	0	1	0	0	0
15	ANOVA (Spreadsheet)	0	0	1	0	0	0
16	STOCHSIM	0	0	1	1	0	0
17	Simio, Flexsim, Edsim	0	0	0	0	3	0
18	Visual SLAM, Process Model, eM-Plant	0	0	0	0	1	0
19	C PROGRAM; MODSIM; INSIGHT; StateCharts; @Risk & excel; Visual Simulation Environment (Orca Computer) simulation language	0	1	0	0	0	0
SD							
1	VENSIM	4	5	0	0	0	0
2	Ithink/Stella	5	4	1	0	0	2
3	DYNAMO	0	1	0	0	0	0
4	Programming Language (Delphi, C++ and VB)	6	0	0	0	0	0
MCRLO							
1	@Risk	0	10	1	0	0	0
2	Crystal ball	0	10	0	0	0	0
3	Microsoft Excel	5	3	0	0	1	0
4	MATLAB	0	2	1	0	1	0
5	TreeAge	0	0	2	0	0	0
6	SAS	0	1	1	0	0	0
7	Miscan (Spreadsheet)	0	1	0	0	0	0
8	Programming Language (QBasic); Massspectrometry (Spreadsheet)	0	0	1	0	0	0
9	SIMHERD; NONMEM; WinBugs	0	2	0	0	0	0
10	RIVRISK; SimTools; Mathematica; BASIC; Stata; Hexalog; JAVA; C11; GENMM.exe; ITOUGH; DATA 3.5 for Healthcare	0	1	0	0	0	0
ABM							
1	NetLogo	0	0	0	0	2	0
2	REDsim	0	0	0	0	1	0
3	Repast simphony	0	0	0	0	0	1
Total (X)		98	98	21	8	84	19

4. Discussion

This umbrella review set out to provide a review of reviews of simulation modelling articles in healthcare. Simulation modelling in healthcare is a diffuse topic, with reviews covering diverse topics and application areas in healthcare. The readers could use this paper as a reference to identify which of these key reviews are best for their research question.

The increase in the number of reviews (and the number of studies included within each review) over time points towards increased interest in the use of these simulation modelling techniques in health care. Also apparent from these reviews is the wide variety of applications, techniques used for simulation modelling, data sources and simulation software used for modelling. Whilst the review is focused on health care in general, many of the questions faced in health technology assessment (HTA) can be addressed using these approaches. These advanced simulation modelling techniques are becoming more popular within HTA and our umbrella review will provide a quick introduction to this field.

However, it should be pointed out that there are some limitations to our approach as it is based on including articles which are considered a systematic review. Whilst there could be encyclopaedias, book chapters, discussion papers, etc that might be useful, we felt peer reviewed articles provided the most robust form of evidence. Similarly, whilst there could be useful opinion pieces, editorials or reviews which handpick a set of relevant articles, we felt they were not as robust as systematically conducted literature reviews. Reviews were only included if they clearly present the review purpose, the search strategy, and the inclusion criteria; and if the article included a detailed description (e.g. at least a paragraph, figure, table or lists of references) of the applied simulation techniques and its application areas from individual studies.

It is possible that there may be studies that are related to simulation modelling in healthcare that were not included in any of the reviews. Simulation studies are published continuously and it is possible that some of them may have been missed depending on the time of publication, the scope of healthcare applications and simulation methods considered in the reviews. On the other hand, studies that were reviewed and synthesised within several of the reviewed articles may skew the total numbers. These issues need to be kept in mind when drawing conclusions regarding the state of the art of simulation modelling in healthcare.

It is possible that there may be other reviews that did not meet our inclusion criteria but may be relevant to simulation modelling in healthcare. There were ten articles that were excluded at the full text review stage as they did not provide information on search strategy, because they were surveys and narrative reviews, not a journal article or reviewed multiple areas (e.g. transportation and retailing alongside healthcare). One of these articles reviewed the use of DES for single and multi-facility healthcare clinics [43], with the other nine articles looked at healthcare systems in general (e.g. hospitals, emergency room, clinics) [44-52]. As no data was extracted from these reviews, the readers may wish to refer to these studies for further information on these topics.

There are other articles which did not meet our inclusion criteria but nevertheless provide an excellent overview of simulation modelling techniques in healthcare. For example, Dangerfield [53] and Wostenholme *et al.* [54] present an overview of system dynamics models for health care in the UK and

Europe. Similarly, there are also application specific review articles such as the review on complex systems modelling for obesity research by Hammon *et al.* [55], complex systems thinking in health disparities research by Diez Roux et al*.* [56], systems science methods (SD, DES and ABM) for public health by Luke *et al.* [57], use of mathematical modelling for infectious diseases by Heesterbeek *et al.* [58] and comparison of different modelling techniques for HIV treatment by Eaton *et al.* [59]. Brennan *et al.* [60] present a taxonomy of the different modelling approaches, which is very useful to understand how the techniques relate to each other. There is also guidance by AHRQ (Agency for Healthcare Research and Quality) regarding model validity assessment [61].

We acknowledge that we were unable to identify an existing tool that is specific to quality assessment of methodology reviews. Nevertheless, we considered it is important to follow recognised systematic review practice and thus to perform some form of quality assessment to differentiate between the quality of included reviews. We therefore added purpose-specific prompts, to address issues specific to simulation modelling reviews, to the AMSTAR instrument while seeking to continue to harness the utility of this previously-validated tool. Further evaluation, in terms of the utility and validity of these minor modifications, is therefore required.

The aim of our review was to provide an overview and understanding of the techniques used for simulation modelling in healthcare but not to provide a synthesis of any specific recommendations. The readers are referred to the individual reviews for these specific recommendations regarding methods or applications. However, it is widely acknowledged that it is difficult to make any blanket recommendation as the choice of the most appropriate methods (e.g. modelling technique) is highly dependent on the decision problem. However, it should be noted that there is guidance on some general principles that need to be considered when selecting a simulation modelling technique for a given healthcare application [62, 63].

5. Conclusions

This paper highlights that simulation modelling has been applied in a wide range of applications in healthcare. The number reviews being published have grown over the years, which point towards increased interest for simulation modelling in healthcare. The studies identified in the reviews use a variety of modelling approaches (DES, SD, ABM), with a variety of software tools and data sources. This umbrella review provides a centralized repository of information for readers to understand the current state of the knowledge for the use of simulation modelling in healthcare, and to identify reviews that best suit any given decision problem.

Data availability statement

All data generated or analysed during this study are included in this published article and its supplementary information file.

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wrote the initial draft, with all authors contributing to the submitted version and also revising the manuscript based on reviewers' comments. SS is the overall guarantor for the manuscript.

Compliance with ethical standards

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