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REVIEW ARTICLE

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 provide an overview of the level of activity of simulation modelling in healthcare and the key themes.

Methods We performed an 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, ScienceDirect) and grey literature sources, enhanced by citation searches. The articles were included if they performed a systematic review of simulation modelling techniques in healthcare. After quality assessment of all included articles, data were 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 (A Measurement Tool used to Assess systematic Reviews) checklist. All the review articles described the types of applications used for simulation modelling; 15 reviews described techniques used for simulation modelling; three reviews described data sources used for simulation modelling; and six 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 recent years suggest an increased interest in simulation modelling in healthcare.

Key Points for Decision Makers

This umbrella review provides a centralised repository of information for readers to understand the current state of knowledge regarding the use of simulation modelling in healthcare.

Simulation modelling techniques have been used to support a wide range of healthcare decision problems, and the number of reviews published recently suggests 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.

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1 Background

There is a large amount of literature on simulation modelling in healthcare and the number of studies has increased over the last 20 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. policy makers, 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. First, 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 has 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.

2 Methods

2.1 Literature Searches

A systematic literature search was conducted in academic databases (JSTOR, Scopus, PubMed, IEEE, SAGE, ACM, Wiley Online Library, ScienceDirect) and other sources for grey literature [Google Scholar, the FreeFullPDF website (http://www.freefullpdf.com), 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 and 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; reviewed the applications of simulation modelling in healthcare; and 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 Measurement Tool used to Assess systematic Reviews) checklist from Shea et al. [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 Electronic Supplementary Material (ESM) Appendix 1.

2.4 Analysis

The data extracted from the reviews were 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 ESM 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, nine for not being in healthcare and 23 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: ten articles as they were not a systematic literature review, six for not being in healthcare, five for using a different definition of simulation and one was 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 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) diagram in Fig. 1.

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 ESM 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, 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 the data extraction stage due to the qualitative nature of the information. The readers are encouraged to refer to ESM 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. Of the 37 included reviews, most achieved a rating of moderate (30 review articles), while the rest exhibited high (three review articles) or low (four review articles) quality ratings. The four articles that 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 ESM 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. First, there is an increase in number of reviews being published with time. There are only two studies published prior to 2005, with five 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.

The 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. discrete-event simulation (DES)] or certain healthcare applications (e.g. emergency departments). For example, reviews by Günal and Pidd [20] and Kammoun et al. [32] look only at studies using DES; Atkinson et al. [34] look at system dynamics (SD); Lakshmi and Sivakumar [31] look at queueing models, while the rest of the reviews are not restricted by specific techniques, i.e. they consider all simulation modelling techniques. On the other hand, as seen in Table 1, the 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 remaining 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 on 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.

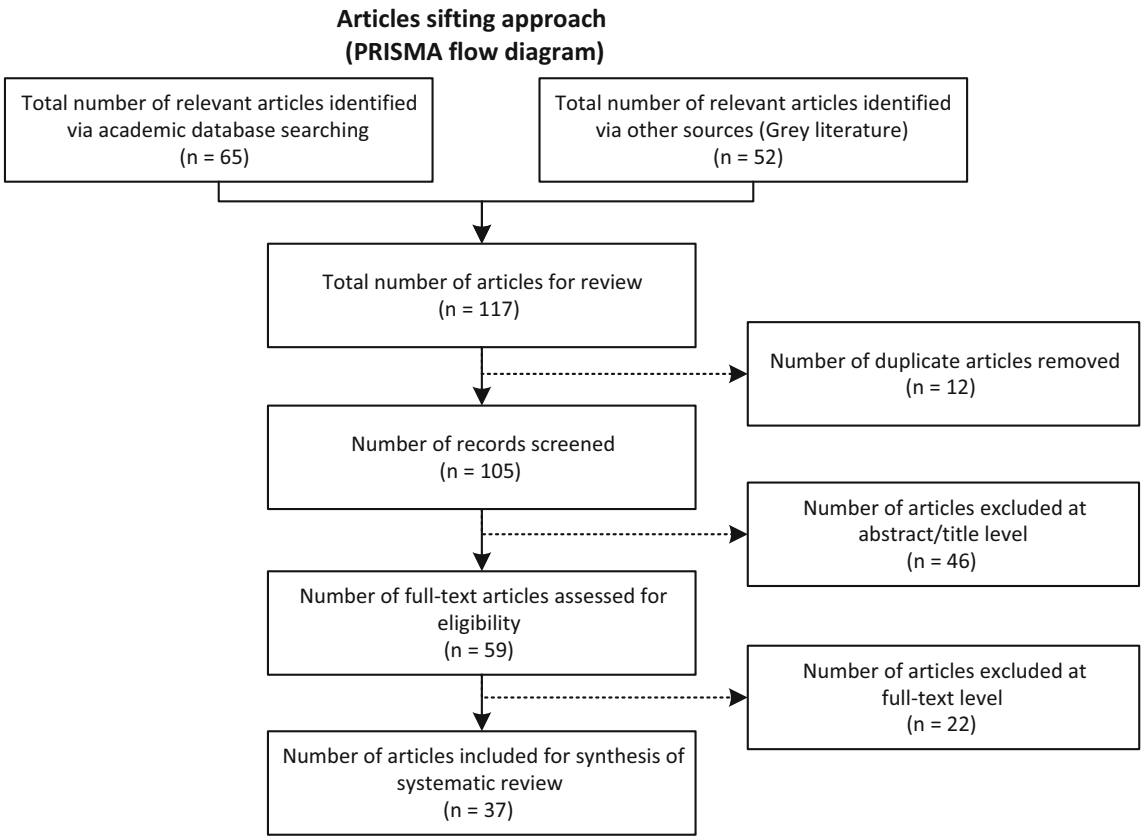

Fig. 1 PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) diagram

Columns 5–8 of Table 1 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, 16–18, 22, 27, 34–37, 39, 41, 42]; three described category 3, data sources used for simulation modelling [9, 15, 37]; and six 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- 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).

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]	Annotated bibliography and review of simulation modelling and healthcare decision making	1981–1992	93	✔			
Fone et al. [8]	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 and Aronsky [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 and Powers [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 and Uzialko-Mydlikowska [14]	Survey of the main trends in the applications of simulation modelling in 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 and Mustafee [18]	Review applications of simulation within the healthcare context	1970–2007	201	✔	✔		✔
Guerriero and Guido [19]	Survey of operational research in the management of the operating theatre	1975–2010	48	✔			
Günal and Pidd [20]	Review of 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 and Mustafee [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 of the relationship between simulation and improvement in hospitals	1997–2008	89	✔			
Beliën and Forcé [25]	Review on inventory and supply chain management of blood products	1966–2010	98	✔			

Table 1 continued

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
Aboueljinane et al. [26]	Review of the use of simulation for the analysis and improvement of emergency medical service	1969–2013	31	✔			
Fakhimi and Probert [27]	Review of 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 and Crema [30]	Review of the tools, practices and guidelines to improve quality and patient safety in healthcare	2004–2013	47	✔			
Lakshmi and Sivakumar [31]	Review of application of queueing theory in healthcare	1952–2011	141	✔			
Mahdavi et al. [2]	Review of generic operational models in healthcare service operation management	1990–2010	116	✔			
Kammoun et al. [32]	Review of the 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 of the use of operation research and/or simulation models in hospital bed management	1998–2013	21	✔	✔		✔
Isern and Moreno [36]	Review of the applications of agents in the healthcare domain	2009–2014	97	✔	✔		
Gul and Guneri [37]	Review of simulation applications of the emergency department for normal and disaster conditions	1968–2013	106	✔	✔	✔	✔
Vieira et al. [38]	Review of operation research methods for logistics optimisation in radiotherapy	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 of the application of validated simulation models in hospital-wide surgical services	2002–2016	22	✔	✔		
Mohiuddin et al. [42]	Review of simulation methods and their contributions for the analysis of patient flow within UK emergency departments	2000–2013	21	✔	✔		✔

SM simulation modelling

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 remaining 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 16 reviews. It should be noted that the data included in the reviews by Mustafee et al. [16] and Katsaliaki and Mustafee [18] were the same and hence are 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 of the studies.

3.3.2 Simulation Techniques Used

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 15 reviews. DES is the most widely used technique, with Monte-Carlo simulation and SD models also commonly used. Agent-based modelling techniques appear to be relatively rare but seem to be coming into more frequent usage 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 cohort simulation techniques. The possible reason for this is that these techniques are commonly combined (e.g. alongside DES or SD techniques) and were not reviewed separately in other reviews.

3.3.3 Data Sources

Out of the 37 simulation articles identified in the umbrella review, only three [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

Table 2 Studies classified by healthcare applications

No.	Classifications of study	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

Table 3 Articles presenting techniques used for simulation modelling

No.	Simulation techniques	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

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

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

No.	Data source for simulation modelling	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

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

studies), secondary data (e.g. literature, questionnaires) as well as expert opinion (e.g. interviews, workshops).

3.3.4 Software Used for Simulation Modelling

Only six 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 technique [DES, SD, Monte-Carlo simulation, agent-based simulation (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.

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 healthcare. 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 healthcare 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 provides 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 that are considered to be 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 that 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 the 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

Table 5 Articles presenting tools used for simulation modelling

No.	Tools for simulation modelling	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

Table 5 continued

No.	Tools for simulation modelling	Studies identified					
		[14] ($n = 168$)	[18] ($n = 201$)	[22] ($n = 70$)	[35] ($n = 21$)	[37] ($n = 106$)	[42] ($n = 21$)
Total (X)		98	98	21	8	84	19

ABM agent-based simulation, *DES* discrete-event simulation, *n* total number of studies reviewed, *MCRLO* Monte-Carlo simulation, SD system-dynamics simulation, *X* total number of studies/results able to perform data/information extraction into categories via the reviewed articles

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 rooms, clinics) [44–52]. As no data were extracted from these reviews, the readers may wish to refer to these studies for further information on these topics.

There are other articles that did not meet our inclusion criteria but nevertheless provide an excellent overview of simulation modelling techniques in healthcare. For example, Dangerfield [53] and Wolstenholme [54] present an overview of SD models for healthcare 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 [55], complex systems thinking in health disparities research by Diez Roux [56], systems science methods (SD, DES and ABM) for public health by Luke and Stamatakis [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 for understanding how the techniques relate to each other. There is also guidance by the 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 that 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, in order 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, not to provide a synthesis of any specific recommendations. The reader is referred to the individual reviews for 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. Nevertheless, 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 of reviews being published has grown over the years, which points towards increased interest in 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 centralised 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 Electronic Supplementary Material.

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Author contributions The study idea originated from PT and was further developed in discussions with SS, and finalised in communication with all authors. SS coordinated the data collection and interpretation, which was agreed among all authors. SS and PT 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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Conflict of interest Syed Salleh, Praveen Thokala, Alan Brennan, Ruby Hughes and Andrew Booth declare that they have no conflicts of interest.

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