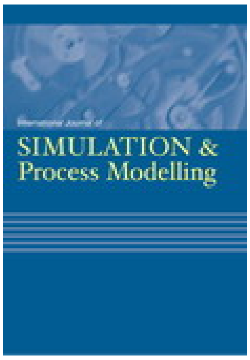

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Abdessalem Jerbi

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The role of discrete-event simulation in emergency management during the COVID-19 pandemic

Abdessalem Jerbi

Laboratoire 'Optimisation, Logistique et Informatique Décisionnelle' (OLID), LR19ES21,
Institut Supérieur de Gestion Industrielle de Sfax,
Université de Sfax,
BP 1164, 3021, Sfax, Tunisia
Email: abdessalem.jerbi@isgis.usf.tn
Email: jerbi_a@yahoo.fr

Abstract: Since its emergence, the COVID-19 pandemic has rapidly evolved into a global health crisis. Despite efforts to contain it, deaths have continued to rise, resulting in profound impacts across all sectors of society. Discrete-event simulation (DES) is a critical tool that helps managing the crisis. This study examines the impact of DES in addressing issues related to the COVID-19 pandemic through bibliometric analysis. The findings show that DES has been widely used to simulate the effective implementation of public health measures, virus spread, and mass vaccination in addressing COVID-19 related issues. However, publications have shown variations over time. Highlighting the importance of DES in responding to the COVID-19 pandemic, this study also identifies key areas where this method can be effectively applied. These results provide valuable insights to guide future efforts in managing this global health crisis.

Keywords: discrete event simulation; DES; performance bibliometric evaluation; COVID-19; global health pandemic.

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Biographical notes: Abdessalem Jerbi is an Associate Professor at the Higher Institute of Industrial Management, University of Sfax, Tunisia (Institut Supérieur de Gestion Industrielle, Université de Sfax, Tunisie). He earned his PhD in 2010 from the National School of Engineers of Sfax, Tunisia (École Nationale d'Ingénieurs de Sfax). His research interests include flexible manufacturing systems, optimization methodologies, discrete-event simulation, design of experiments, and scheduling rules.

1 Introduction

In 2019, the world witnessed the emergence of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), more commonly known as COVID-19, with its epicentre traced back to Wuhan, China. By January 2020, the World Health Organization (WHO) declared COVID-19 a pandemic due to its rapid transmission and high infectivity.

Despite extensive efforts to control the COVID-19 epidemic, conclusive results have remained elusive. As of April 2022, there were 500,186,525 confirmed cases worldwide, resulting in 6,190,349 deaths (WHO, 2024). Subsequently, mass vaccination campaigns were launched globally following the development of several vaccines. While these efforts mitigated the severity of the epidemic, new waves emerged with the emergence of COVID-19 variants, leading to ongoing increases in cases and fatalities. As of January 2024, WHO reported a total of 774,593,066 confirmed cases and 7,028,881 deaths (WHO, 2024).

Beyond its toll on public health, the COVID-19 pandemic has profoundly affected all sectors of society, triggering a global economic downturn. Moreover, the pandemic's resolution remains uncertain due to limited vaccine supplies and the efficacy of developed vaccines. Therefore, leveraging available data and appropriate tools is imperative for policymakers, health officials, industries, and other sectors to effectively manage this crisis, especially amidst the uncertainty posed by viral mutations and their impacts on intervention strategies.

Simulation tools are widely used operational research techniques, including standard Petri nets, coloured Petri nets (CPNs), agent-based simulation (ABS), system dynamics (SD) and discrete-event simulation (DES). Each of these tools offers unique strengths in modelling and analysing complex systems. Standard Petri nets are strong in capturing process control flow, concurrency, and resource sharing, making them valuable in business process modelling. However, they struggle with quantitative aspects like time or performance metrics, limiting their usefulness in resource optimisation. CPNs add complexity by modelling detailed data flows and interactions between entities, though they become cumbersome in large systems and are less effective for performance analysis. ABS excels in modelling individual behaviours and interactions in dynamic systems, but it can be computationally expensive and lacks structured control flow. SD is ideal for long-term, aggregated system behaviour and feedback analysis but is unsuitable for event-driven, time-sensitive systems. In contrast, DES is highly effective for modelling dynamic, time-based systems and resource management. DES stands out in optimising production processes, healthcare capacity planning, and operational simulations by enabling detailed performance analysis and resource allocation. Although it may be computationally intensive and less graphical than Petri nets, DES offers superior capabilities for time-sensitive decision making and operational-level system analysis, making it a leading technique for managing complex, resource-dependent processes. DES is widely utilised in enhancing production processes, healthcare capacity planning, program evaluations, and investment decision assessments (Collins et al., 2023; Zhang and Lin, 2023; Leoni et al., 2023; Monks and Harper, 2023; Wang and Liao, 2023; Rotunno et al., 2023; Alkabaa, 2022; Maclean and Mohamed, 2022; Orozco et al., 2022; Ershadi and Shafaeizadeh, 2021), DES has also played a crucial role during the COVID-19 pandemic. It has been employed to optimise resource allocation, design and evaluate public health policies (Perez-Tezoco et al., 2023; Xu et al., 2023; Werner, 2023; Moreira et al., 2023; Possik et al., 2023; Sala et al., 2023; Jerbi and Masmoudi, 2023), among other applications.

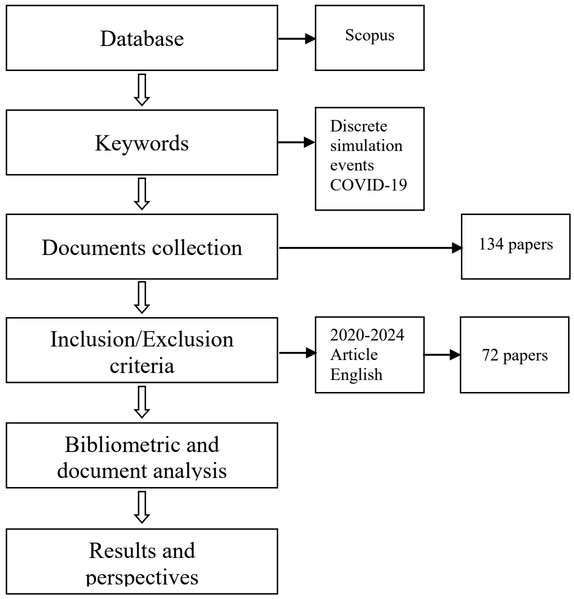
This study explores the role of DES during the COVID-19 pandemic through the lens of bibliometric analysis, a method selected for its robustness in quantifying and visualising research trends. Bibliometric analysis was chosen not only for its ability to capture the breadth and evolution of research but also to highlight key contributors, influential works, and collaborative networks that have shaped the application of DES during the pandemic. By identifying research gaps, emerging themes, and dominant methodologies, this approach provides valuable insights into how DES has contributed to addressing the complex, global challenges posed by COVID-19. Moreover, bibliometric analysis enables the assessment of research impact, offering a data-driven understanding of the field's trajectory over time. The study aims to meet three key research objectives: first, to conduct a bibliometric analysis of COVID-19-related studies employing the DES method (RO1), and second, to perform a structural analysis of this research (RO2). Together, these objectives will help elucidate the significance and impact of DES in the pandemic context, reinforcing the importance of data-driven decision making in crisis management.

The rest of this study is structured as follows: Section 2 presents the methodology, including the bibliometric analysis framework, data collection processes and procedures, and analysis techniques. Section 3 presents and discusses the results of the bibliometric analysis. Section 4 provides an analysis of the applications of DES in addressing the COVID-19 health crisis. The final section concludes the article and identifies potential future research directions.

2 Method

The literature review on the utilisation of DES in response to the COVID-19 outbreak was undertaken using a systematic analysis approach, involving several phases outlined in Figure 1.

Figure 1 Workflow of the literature review process for identifying relevant studies on DES applications during the COVID-19 pandemic



The analysis utilises the Scopus database, renowned as one of the largest repositories of peer-reviewed literature globally, encompassing a vast array of titles and publishers across numerous fields. This database offers a comprehensive insight into worldwide research output. To thoroughly examine the role of DES in mitigating the COVID-19 health crisis, a set of keywords was crafted in conjunction with 'COVID-19' to initiate the search process. The query was structured to target specific terms within the title, abstract, and keywords fields, encompassing variations of 'discrete', 'simulation', 'event' and COVID-19-related terms ('nCoV', 'SARS-CoV-2', 'coronavirus').

The search parameters were meticulously defined, including criteria such as publication year (2020–2024), publication type (limited to articles), and language (English). This yielded an initial pool of 134 articles. Subsequent screening involved a comprehensive assessment of abstracts to ascertain alignment with the study's objectives. This led to the exclusion of 62 articles that did not closely correspond to the focus of the bibliographic study, resulting in a final selection of 72 studies.

These studies were further categorised based on their primary objectives, revealing three overarching themes:

management of public healthcare systems, containment strategies, and mass vaccination initiatives. Of the 72 articles, 44 (61.11%) applied DES in public healthcare management, while 21 studies (29.16%) utilised DES to model the spread of COVID-19 and control contamination. Additionally, seven articles (9.72%) employed DES to model, analyse, and optimise mass vaccination centres.

3 Bibliometric analyses

Bibliometric studies are dedicated to conducting statistical analyses of publications, aiming to monitor and assess research trends and the performance of related works. These analyses utilise a range of indicators to illustrate connections between published documents and their content (van Leeuwen, 2004; Donthu et al., 2021). Performance metrics employed in such analyses encompass publication trends, citation impacts, and occurrences of keywords, all of which aid in identifying prevailing research themes and trends. Additionally, author analysis is instrumental in highlighting key contributors and evaluating their productivity (Yan and Ding, 2012).

The identified documents were extracted as metadata in text format and subsequently imported into 'Bibliometrix', an R-based software application, for thorough analysis and visualisation. Among the 72 documents analysed, 33 sources were dedicated to healthcare management, 17 focused on studies related to virus propagation management, and seven delved into studies on mass vaccination management against COVID-19. These documents were authored or co-authored by 279, 106 and 23 individuals respectively (Table 1).

Table 1 Summary of the contribution of DES to solving problems related to the COVID-19 pandemic

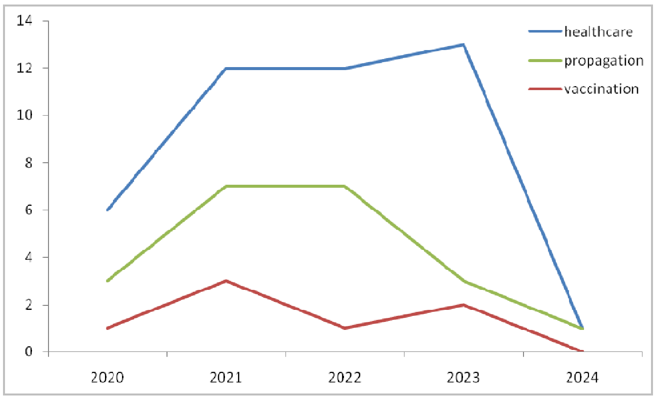
Description		*Results*	*Description*		*Results*
Years of publications	H	2020–2024	Authors	H	279
	P	2020–2024		P	106
	V	2020–2024		V	23
Total publications	H	44	Authors of single authored docs	H	2
	P	21		P	1
	V	7		V	0
Sources	H	33	Co-authors per doc	H	6.48
	P	17		P	5.67
	V	7		V	4.14
Annual growth rate	H	–36.11	Keywords	H	468
	P	–24.02		P	175
	V	25.99		V	90
Document average age	H	2.2	Average citations per doc	H	6.818
	P	2.38		P	5.095
	V	2.43		V	16.57

Note: H – healthcare, P – propagation, V – vaccination.

3.1 *Examination of publication trends*

The analysis of publication trends reveals the annual growth rate of scientific production for articles utilising DES to tackle issues surrounding the COVID-19 pandemic between 2020 and 2024. Notably, there are two negative growth rates of –36.11% and –24.02% for healthcare and virus spread management, respectively, while a positive growth rate of 25.99% is observed for mass vaccination (Table 1). On average, there are 11, 5.25 and 1.75 articles published per year for healthcare, virus spread, and mass vaccination, respectively. The peak in publication numbers occurred in 2021. Figure 2 illustrates the annual scientific production utilising the DES technique for managing healthcare systems, virus spread, and mass vaccination in relation to COVID-19 from 2020 to 2024.

Figure 2 Annual scientific productions of publications utilising DES techniques from 2020 to 2024 in the context of COVID-19 pandemic management (see online version for colours)



The notable negative growth rates for healthcare and virus spread management can be attributed to several factors:

- Pandemic recovery and shifts in focus: as societies began to recover from the pandemic, the urgency surrounding immediate COVID-19 challenges diminished. Research priorities may have shifted towards long-term health implications, post-pandemic recovery strategies, and other pressing public health issues, leading to a decline in publications directly focused on the pandemic.
- Saturation of existing research: by 2021, a peak in publication numbers may have resulted in an oversaturation of literature related to COVID-19 management through DES. As foundational research became established, the need for additional studies may have decreased, particularly in areas such as healthcare and virus spread management.
- Funding and resource allocation: funding agencies and research institutions may have redirected their resources towards other emerging health crises or priorities. As the pandemic's immediate threats receded, funding opportunities for COVID-19-related research, especially for specific methodologies like DES, may have diminished.

- Shifting research interest: researchers may be moving towards more innovative or emerging methodologies, diverting attention from DES in the context of COVID-19. This shift could be influenced by the desire to explore new avenues of inquiry or to address other health crises that have gained prominence.
- Consolidation of findings: the body of research utilising DES for COVID-19 management may have reached a point where the existing findings sufficiently addressed critical issues, resulting in fewer new studies being necessary. Researchers may have opted to synthesise and analyse existing literature rather than conduct new studies.

In contrast, the positive growth rate observed for mass vaccination highlights a continued interest in this critical aspect of pandemic response. The emphasis on vaccination efforts remains crucial in the fight against COVID-19 and is likely to attract ongoing research and publication activity.

3.2 Analysis of publication citations

Analysing publication citations serves to assess the impact, relevance, and influence of research within a specific field. It allows researchers to identify key trends and emerging areas of interest, while also evaluating the impact of individual publications or authors based on citation frequency. Additionally, it enables the identification of knowledge gaps by highlighting underexplored topics that may require further investigation. Ultimately, citation metrics reflect the scholarly influence of research, shaping future studies, practices, and policies.

The examination of publications reveals average citation rates of 6.818, 5.095, and 16.57 citations per document for healthcare management; virus spread management, and mass vaccination in the context of combating the virus (Table 1). Additionally, the respective citation totals for each topic during the pandemic years are 300, 107 and 116 (Table 2).

The analysis findings indicate that during the pandemic years, a notable proportion of publications received no citations, with approximately 18.18%, 14.28%, and 0% falling into healthcare management; virus spread management, and mass vaccination category. Moreover, 61.36%, 61.90%, and 42.85% respectively obtained between 1 and 9 citations, while a smaller percentage, 6.8%, 19.04%, and 0% respectively received more than ten citations but less than 20 citations. Notably, the number of articles receiving 20 or more citations is limited, with only a few standout pieces. Specifically, two articles each in healthcare management and mass vaccination category accrued over 30 citations, with an additional two articles garnering over 50 citations each. Conversely, no articles addressing virus spread management received more than 20 citations (Table 2).

In summary, a substantial percentage of articles focusing on healthcare and virus spread management topics, 82% and 86% respectively, were cited, underscoring their significance in scholarly discourse. Furthermore, all articles employing DES for managing mass vaccination centres against COVID-19 received citations, highlighting their recognised contributions. Considering the duration of the citation years, these attained citations carry substantial weight in reflecting the impact and relevance of the research.

Several factors may explain these citations trends:

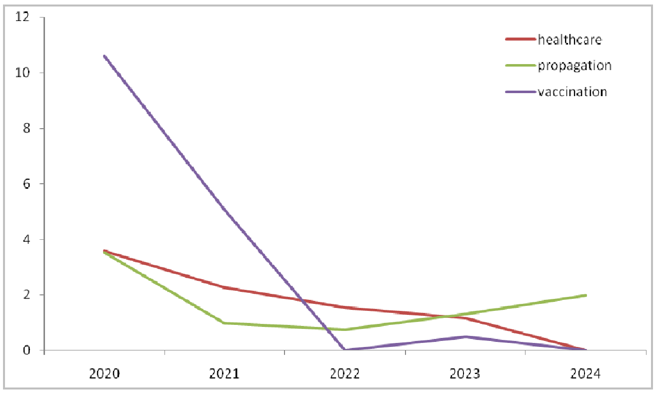
- Variability in research impact: articles related to healthcare management and virus spread management may have varying contributions. If certain studies do not present significant findings or novel perspectives, they are less likely to be cited frequently. In contrast, research on mass vaccination, addressing a crucial and urgent topic, may attract more attention and citations.
- Publication saturation: as the number of published articles increased during the pandemic, competition for researchers' attention also intensified. This saturation can lead to a reduced number of citations per article, as researchers may focus on the most recent or innovative studies, leaving others overlooked.
- Shifting research priorities: research priorities may have evolved over time. While the world initially focused on healthcare management and virus spread, emphasis may have shifted towards vaccination strategies, resulting in fewer citations for older or less relevant publications in the current context.
- Emerging methodologies and knowledge: the dynamic nature of COVID-19 research may have prompted researchers to adopt new methodologies or explore different avenues of inquiry. If previous articles did not employ innovative methods, they might be cited less frequently.
- Temporal relevance of publications: publications that address urgent or ongoing issues, such as mass vaccination, tend to be cited more than those that examine resolved matters. Articles on virus spread management, which may be perceived as less urgent following the initial waves of the pandemic, might have received less attention.

Table 2 Citation analysis of publications on the application of DES in solving the health crisis related to COVID-19

Number of citations	*>=50*	*>=40*	*>=30*	*>=20*	*>=10*	*>=1*	*=0*	*Total citations*	*Total cited*
Healthcare	1	0	1	4	3	27	8	300	82%
Propagation	0	0	0	1	4	13	3	107	86%
Vaccination	1	0	1	1	0	3	0	116	100%

Figure 3 depicts the trend curves of average citations per year across the three categories of DES application in addressing COVID-19-related issues. Notably, the highest average citation rate was observed in the mass vaccination category, with articles garnering 10.6 citations in 2020. However, this trend exhibits a significant decline in subsequent years. In 2020, articles focusing on virus propagation management and mass vaccination against the virus received comparable citation averages of 3.57 and 3.53, respectively. Subsequently, their citation trends diverge. Specifically, the citation trend for healthcare management articles continues to decline in subsequent years, reaching zero by 2024. Conversely, the citation trend for articles addressing mass vaccination against COVID-19 experiences a slight decrease from 2020 to 2021, stabilises in 2022, and then exhibits an upward trend in 2023 and 2024.

Figure 3 Average citation per year (see online version for colours)



Several factors may explain these average citations per year trends:

- Initial surge in interest: the spike in citations for mass vaccination articles in 2020 can be attributed to the urgent global focus on developing and implementing vaccination strategies in response to the COVID-19 pandemic. This urgency likely led to increased interest and citations as researchers sought to reference key studies that informed vaccination efforts.
- Diverging trends: in 2020, articles on virus propagation management and mass vaccination received comparable citation averages. However, as the pandemic evolved, the citation trends began to diverge. The decline in citations for healthcare management articles can be linked to the oversaturation of literature in that area, diminishing the perceived novelty or relevance of new studies as researchers shifted focus toward more pressing issues.
- Stabilisation and recovery of mass vaccination articles: while citations for healthcare management articles continue to decline, the trend for mass vaccination articles demonstrates resilience. After a slight decrease from 2020 to 2021, these articles stabilised in 2022, indicating sustained interest. This stabilisation may reflect ongoing discussions and research surrounding vaccination strategies, effectiveness, and public health implications as vaccination campaigns became a central component of pandemic response.
- Rising importance of mass vaccination: the upward trend in citations for mass vaccination articles in 2023 and 2024 suggests a renewed interest in this area. Factors contributing to this trend may include the ongoing evaluation of vaccination programs, new studies investigating booster shots, variants of the virus, and long-term vaccine effectiveness. As governments and health organisations continue to navigate vaccination strategies, the relevance of this research remains significant, leading to increased citations.
- Declining relevance of healthcare management: the complete decline to zero citations for healthcare management articles by 2024 indicates that research in this area may no longer be perceived as impactful or relevant to current challenges. As the pandemic evolved, priorities may have shifted towards topics like vaccination, new variants, and long-term health impacts, overshadowing earlier work in healthcare management.

The most cited publications include those by Wood et al. (2020) in healthcare, Kierzkowski and Kisiel (2020) in virus propagation management, and Asgary et al. (2020) in mass vaccination management against COVID-19 categories. These studies have amassed 50, 26, and 53 citations, respectively, since their publication. Table 3 provides comprehensive results, detailing the total number of citations, average citation per year, and total normalised citation count.

When considering the average citation per year, the articles with the highest average citations per year align with those possessing the highest total citation counts. However, the ranking of other articles based on this metric may vary. In the category of healthcare management studies, for example, the research by Garcia-Vicuña et al. (2022) outperforms that of Bardet et al. (2021) with an average of 7 citations per year, despite being more recent. Similarly, the study by Tavakoli et al. (2022) surpasses those of Das (2020) and Zeinalnezhad et al. (2020) with an average citation rate of 5.33 per year, even though it was published two years later. For studies addressing COVID-19 virus propagation management category, recent research such as that by Schmidt and Albert (2022) and Possik et al. (2023) demonstrates higher average citations per year compared to older studies like those by Cimini et al. (2021) and Lim et al. (2020). For studies addressing mass vaccination operations against COVID-19 category the order of superiority of the average citations per year remains the same as that of the total citation count.

Table 3 Most cited publications on the application of DES in addressing the COVID-19 health crisis

Paper	*TC*	*TC/Y*	*NTC*
Healthcare			
Wood et al. (2020)	50	10	2.80
Melman et al. (2021)	35	8.75	3.89
Bardet et al. (2021)	23	5.75	2.56
Garcia-Vicuña et al. (2022)	22	7.34	4.80
Das (2020)	21	4.2	1.18
Zeinalnezhad et al. (2020)	21	4.2	1.18
Tavakoli et al. (2022)	16	5.33	3.49
Sethi et al. (2021)	10	2.5	1.11
Gardiner et al. (2020)	10	2	0.56
El Hage et al. (2021)	9	2.25	1
Shahverdi et al. (2023)	8	4	3.47
Bovim et al. (2023)	7	3.5	3.04
Propagation			
Kierzkowski and Kisiel (2020)	26	5.2	1.47
Lim et al. (2020)	17	3.4	0.96
Allen et al. (2020)	10	2	0.57
Tofighi et al. (2021)	10	2.5	2.5
Schmidt and Albert (2022)	10	3.34	4.38
Cimini et al. (2021)	8	2	2
Possik et al. (2023)	5	2.5	1.86
Vaccination			
Asgary et al. (2020)	53	10.6	1
Asgary et al. (2021a)	30	7.5	1.48
Pilati et al. (2021)	22	5.5	1.08
Asgary et al. (2021b).	9	2.25	0.44

Note: TC – total citation, TC/Y – total citation per year, NTC – normalised total citation.

To enhance fairness, we have embraced the total normalised citation count (NTC). This metric serves as a benchmark for assessing a publication's significance by comparing its citations to the average received by similar works globally within the same field and year (Kreiman and Maunsell, 2011; Waltman, 2016). An NTC exceeding 1 indicates that a document garners citations beyond what is typical for its peers. Moreover, the NTC facilitates equitable comparisons across studies, irrespective of variations in publication rates, disciplinary focuses, dates, and types. Results showed that Garcia-Vicuña et al. (2022) stands out with the highest NTC among all studies focusing on healthcare operations during the COVID-19 crisis. Interestingly, the hierarchy shifts when compared to total citation counts. For instance, Tavakoli et al. (2022), ranked seventh in total citations, climbs to the third spot in terms of NTC. Notably, nearly all studies boast NTC values exceeding 1, barring Gardiner et al. (2020), despite its early publication. Similar trends emerge in studies addressing COVID-19 virus propagation management, where Schmidt and Albert (2022) lead with the highest NTC, surpassing Allen et al. (2020), despite equal citation counts. Allen et al. (2020) even exhibit an NTC below 1. In studies concerning mass vaccination operations, the hierarchy shifts slightly compared to total citation counts, with only the order of Asgary et al.'s (2020, 2021a) studies interchanging, while the ranking of others remains unchanged. Furthermore, only Asgary et al. (2021b) record an NTC below 1.

Analysing the NTC rankings across three categories of DES application during the COVID-19 crisis reveals that studies focusing on healthcare management exhibit the highest NTC. This suggests a notable researcher interest in tackling healthcare-related challenges over other domains. Conversely, studies centred on mass vaccination operations against COVID-19 display the lowest NTC, albeit still exceeding 1. This trend could be attributed to the limited number of studies addressing this specific issue, making them more likely to be cited within their domain.

3.3 Analysis of relevant authors

Analysing relevant authors serves to identify key contributors and thought leaders within a specific field. This analysis highlights the most influential authors whose work significantly impacts the research area, while also tracking their research contributions through publication output and citation patterns. It maps the intellectual influence of authors, showing how they shape the direction of the field through their publications and collaborations. Additionally, identifying relevant authors facilitates potential partnerships between researchers with shared interests or complementary expertise. By analysing key authors, researchers can also uncover evolving research trends and emerging areas of study.

Table 4 highlights the most relevant authors based on their study contributions, while acknowledging that additional authors, not listed, contributed to individual studies. Healthcare studies engaged 279 authors, virus propagation studies involved 106 authors, and mass vaccination studies targeting COVID-19 included 23 authors. Several of these prominent authors played key roles in multiple studies across various research areas addressing the COVID-19 health crisis. For instance, Asgary A., Najafabadi M.M. and Wu J. each participated in the authorship of three virus propagation studies and three mass vaccination studies against COVID-19, totalling six studies each.

In order to accurately evaluate authors' contributions to published studies, their inputs were weighted based on the number of authors per article. Author productivity was then calculated by summing their contributions across publications using the 'fractionalised articles' index (Korytkowski and Kulczycki, 2019; Hagen, 2014). This approach allows for a comprehensive assessment of authors' efforts in study development, assuming uniform contribution from all co-authors. According to this index, authors Das A., Swinarski D., and Werner C. emerge as the most relevant. Notably, these authors are associated with single-author documents (Table 4). This is unsurprising, as these individuals independently managed all aspects of their respective publications, reflecting their sole authorship.

Table 4 Most relevant authors of DES studies in addressing the COVID-19 health crisis

Authors	*Articles*	*Articles fractionalised*
Asgary A.	3V + 3P	0.62 + 0.25 = 0.87
Najafabadi M.M.	3V + 3P	0.62 + 0.25 = 0.87
Wu J.	3V + 3P	0.62 + 0.25 = 0.87
Tofighi M.	3P	0.25
Aarabi M.	2P	0.18
Esparza L.	2H	0.50
Kirsch T.D.	2H	0.41
Mallor F.	2H	0.50
Miller-Hooks E.	2H	0.42
Nadri N.	2P	0.18
Prentiss D.	2H	0.42
Shafiee M.A.	2P	0.18
Tariverdi M.	2H	0.42
Zhao Q.	2P	0.50
Zhu H.	2P	0.42
Das A.	1H	1
Swinarski D.	1P	1
Werner C.	1H	1

Note: H – healthcare, P – propagation, V – vaccination.

3.4 Analysis of relevant sources

The analysis of relevant sources aims to achieve several key objectives such as the credibility, by evaluating the reliability and validity of the analysed sources to ensure the information is credible and well-founded and the contextual understanding, where relevant literature, studies, and data are discussed to provide a foundation for the research question or hypothesis. Additionally, this analysis seeks to identify gaps in the existing literature, thereby justifying the necessity of the current study. Lastly, it involves a synthesis of information, drawing connections between various findings to elucidate their contributions to the overall understanding of the subject. Together, these objectives enhance the rigor and relevance of the research.

During the COVID-19 health crisis, 72 articles were published across various sources, with healthcare articles distributed among 33 sources, virus propagation studies among 17 sources, and mass vaccination studies against COVID-19 among 7 sources. Table 5 highlights the most relevant sources based on article count, with these sources collectively accounting for 34 articles (47.22%), contributing to 303 citations out of 523 (57.93%). The remaining sources each published only one article.

It is interesting to note the variety of journals that have focused on publishing DES studies amid the COVID-19 health crisis. While some journals specialise in simulation, such as the *Journal of Simulation*, many others publish research on healthcare delivery, management, and policies, such as *Healthcare Analytics*, *Health Care Management Science*, *Healthcare (Switzerland)* and *International Journal of Environmental Research and Public Health*. Some journals focus on related objectives, such as public health preparedness and disaster response, as seen in the *Disaster Medicine and Public Health Preparedness* journal, while others emphasise system evaluation in healthcare environments through medical informatics, as evident in the *International Journal of Medical Informatics*.

Table 5 Most relevant sources with most studies in addressing the COVID-19 health crisis

Source	*NP*	*Type*	*TC*
JOURNAL OF SIMULATION	5	2H + 3P	16
PLOS ONE	5	2H + 3P	34
BMJ OPEN	3	3H	7
HEALTHCARE ANALYTICS	3	3H	5
HEALTH CARE MANAGEMENT SCIENCE	3	3H	87
HEALTHCARE (SWITZERLAND)	3	1H + 1P + 1V	63
DISASTER MEDICINE AND PUBLIC HEALTH PREPAREDNESS	2	2H	9
IEEE TRANSACTIONS ON AUTOMATION SCIENCE AND ENGINEERING	2	2H	1
INTERNATIONAL JOURNAL OF ENVIRONMENTAL RESEARCH AND PUBLIC HEALTH	2	1H + 1V	51
INTERNATIONAL JOURNAL OF MEDICAL INFORMATICS	2	1H + 1V	5
JOURNAL OF THE OPERATIONAL RESEARCH SOCIETY	2	2H	3
SUSTAINABILITY (SWITZERLAND)	2	1P + 1V	22

Note: H – healthcare, P – propagation, V – vaccination, NP – Number of publication, TC – total citation.

It is noteworthy that the *Journal of the Operational Research Society*, given its focus on operations research, naturally gravitates towards publishing articles on DES amid the COVID-19 crisis. However, the interest shown by journals like *Sustainability* is unexpected. Despite defining itself as an interdisciplinary review focusing on various aspects of human sustainability, its open-access nature may justify this interest, especially considering the participation of other open-access journals such as *PLOS ONE* and *BMJ Open* in this publishing effort.

Table 6 Most relevant keyword clusters identified in DES studies addressing the COVID.19 pandemic

Keywords	*Occurrences*
Healthcare	
covid-19, covid-19 pandemic, coronavirus disease 2019, coronavirus infection, coronavirus infections, betacoronavirus, sars-cov-2	70
discrete event simulation, discrete-event simulations, discrete events simulation, computer simulation, simulation, discrete-event simulation model	48
human, humans	47
pandemic, pandemics	42
hospital, hospitals, university hospital, hospital management, general hospital, hospital administration, hospital planning, hospital pandemic planning, hospital sector, public hospital, hospital admission	22
article	19
intensive care, intensive care unit, intensive care units	16
decision making, decision support system, decision support systems, decision aids, decision makers, decision supports, decisions makings	13
organisation and management, organisational	10
health care management, health care organisation, health care planning, health care policy, health care system, health promotion	10
Propagation	
discrete event simulation, discrete-event simulations, computer simulation, simulation approach, simulation model, simulation platform, hybrid simulation	27
covid-19; sars-cov-2, betacoronavirus, coronavirus disease 2019	19
human, humans	11
pandemic, pandemics	10
computational methods, computational modelling	7
Vaccination	
discrete event simulation, discrete-event simulations, simulation, simulation studies, computer simulation, simulation-modelling, simulation model	16
mass immunisation, mass vaccination, vaccination, immunisation, mass vaccination center	16
covid-19, coronavirus disease 2019, sars coronavirus, coronavirus	12
vaccines, sars-cov-2 vaccine, covid-19 vaccines	4

3.5 Analysis of keywords

Keyword analysis plays a crucial role in identifying the core themes, trends, and focal areas within a specific research domain. It enables researchers to pinpoint the dominant topics and concepts that shape the field while also tracking emerging trends and areas of growing interest over time. Furthermore, keyword analysis significantly enhances the efficiency of literature searches by refining search strategies and identifying the most relevant and frequently used terms, thereby facilitating the discovery of pertinent studies and information.

A total of 468 keywords were associated with studies employing DES for healthcare operations management, while 175 keywords were linked to studies focusing on DES for virus propagation management, and 90 keywords were related to studies utilising DES for mass vaccination management against COVID-19. Regarding their frequency of occurrence, 327 (70%), 132 (75%) and 68 (75%) terms appeared once, 76 (16%), 18 (10%) and 10 (11%) appeared twice, and 17 (3.6%), 11 (6.3%) and 1 (1.1%) appeared three times, respectively. Additionally, nearly 9.4%, 5.1%, and 10% of the keywords appeared four times or more. Given that some keywords exhibited similarity across different writings; they have been categorised based on their degree of resemblance. Table 6 presents the most commonly used keyword clusters in studies utilising DES to address the COVID-19 health crisis. Notably, the ‘COVID-19’ keyword cluster consistently dominates in terms of occurrences across various study types, closely followed by the ‘discrete-event simulation’ cluster. Furthermore, specific keyword clusters emerge based on the research context, such as the ‘HOSPITAL’ cluster for healthcare management studies, the ‘PANDEMIC’ cluster for virus propagation management studies, and the ‘VACCINATION’ cluster for mass vaccination management studies against COVID-19.

4 Analysis of DES applications in addressing the COVID-19 health crisis

4.1 Public health systems management

4.1.1 Simulated infrastructures

Various medical infrastructures have been modelled using discrete event simulation. Among these infrastructures are primarily hospitals (Zhang et al., 2023; Redondo et al., 2023; Xu et al., 2023; Miller-Hooks et al., 2022; Warde et al., 2021). Other specific medical infrastructures have been simulated during the COVID-19 crisis, such as intensive care units (Ortiz-Barrios et al., 2023; Redondo et al., 2023; Shahverdi et al., 2023), chronic obstructive pulmonary disease care units (Yakutcan et al., 2022), abdominal aortic aneurysm screening services (Kim et al., 2021b), surgical departments (Abdullah et al., 2021; Melman et al., 2021), emergency units (Bovim et al., 2023), an ambulatory endoscopy centre (Das, 2020), or imaging departments (Sala et al., 2022). In some cases, simulation studies have focused on specific types of clinics, such as heart disease clinics (Zeinalnezhad et al., 2020; Kim et al., 2021a), cancer disease clinics (Smith et al., 2022; Bardet et al., 2021), or a retinal clinic (Sethi et al., 2021). The last category of simulated medical structures includes COVID-19 testing centres (Gowda et al., 2021).

4.1.2 Objectives of simulations

These infrastructures were simulated to explore various specific objectives. The primary objective studied was the examination of hospital resource planning (Lay et al., 2023; Wood et al., 2020; Shahverdi et al., 2023; Garcia-Vicuña et al., 2022; Chalk et al., 2021; Saidani and Kim, 2021). Several studies then explored the planning and utilisation of specific resources such as beds in the context of the COVID-19 crisis (Zhang et al., 2023; Redondo et al., 2023; Ortiz-Barrios et al., 2023; Bovim et al., 2023; García-Vicuña et al., 2020; Miller-Hooks et al., 2022; Campos et al., 2023). Frichi et al. (2022) studied the impact of increasing hospital capacities to conduct large-scale testing on pandemic control by reducing COVID-19 testing time. A simulation approach was adopted by Faccincani et al. (2022) to evaluate and compare different adaptive resource allocation strategies of a hospital in response to a sudden mass casualty incident. Conlon and Molloy (2023), Qureshi et al. (2024), Çaglayan et al. (2022) and Das (2020) generated metrics related to nurses' daily workload to examine how COVID-19 patient care affects human resource workload. Zimmerman et al. (2023) explored through discrete event simulation the capacity planning of ventilators during the first wave of the COVID-19 epidemic.

The second objective of discrete event simulation studies in medical infrastructures is the study of patient flow (Perez-Tezoco et al., 2023; Xu et al., 2023; Werner, 2023; Smith et al., 2022; Yakutcan et al., 2022; Nehme et al., 2022; Kohler et al., 2022; Tavakoli et al., 2022; Sethi et al., 2021; Kim et al., 2021a; Bardet et al., 2021; Melman et al., 2021; Zeinalnezhad et al., 2020). Some researchers focused on patient waiting time, as illustrated by Xu et al. (2023), while others explored estimating the number of possible admissions, as demonstrated in Yakutcan et al. (2022) study. Additionally, some identified bottlenecks in the flow of COVID-19 patients, as done in Zeinalnezhad et al. (2020) study. Other researchers adopted an approach focused on modelling the effects of uncertainty regarding arrival numbers on the performance of the structures studied, as examined by Werner (2023). Similarly, Kohler et al. (2022) studied the vulnerability of a hospital to small increases in patient numbers, while Tavakoli et al. (2022) attempted to predict future patient flows in a hospital to estimate its capacity to withstand such pressures. From another perspective, Sethi et al. (2021) sought to model a clinic's future flow to anticipate its operational performance under increasing patient volumes. Nehme et al. (2022) and Kim et al. (2021a, 2021b) explored patient arrival management. The first study attempted to prioritise patients and predict delays on the post-COVID-19 waiting list; the second study examined the impact of delayed invitation and reduced male attendance at screening, while the third study sought to effectively sort COVID-19 patients in contexts of limited data. They also explored optimal resource thresholds to minimise mortality rates while maintaining healthcare system capacity. Finally, Peng et al. (2020) evaluated the impact of using a triage physician on patient waiting times in an emergency department.

A third category of studies focused on managing specific infrastructures such as COVID-19 testing centres or surgical departments. Guan et al. (2022), El Hage et al. (2021) and Gowda et al. (2021) then modelled the process of testing centre operations through discrete event simulation. The former sought to minimise the total time samples spent as well as equipment consumption. The second aimed to facilitate the rapid expansion of testing capacity during a public health emergency. The third identified, through a simulation model, bottlenecks in the throughput of a testing centre with limited resources. Abdullah et al. (2021) and Warde et al. (2021) on their part modelled general surgery services. The former evaluated different strategies for cancelling elective surgeries and recovery scenarios on several operational outcomes, while the latter sought to approximate the weekly effect of adjusting surgical volume on hospital census. Finally, Sala et al. (2022) examined the impact of COVID-19 containment policies on the performance of a diagnostic imaging department of an outpatient facility through direct comparison of key performance indicators measured in both ordinary and pandemic scenarios.

4.2 Management of virus propagation

4.2.1 Simulated infrastructures

The propagation of COVID-19 has been modelled and studied in various facilities, including hospital settings such as hospital intensive care units (Possik et al., 2023), dialysis services (Allen et al., 2020; Tofighi et al., 2021), and biological analysis laboratories (Lim et al., 2020).

Educational institutions, such as universities, have been simulated to model individual behaviours over time and space, as well as to assess the effectiveness of COVID-19 propagation control measures adopted during the pandemic (Cimini et al., 2021; Swinarski, 2021; Qiu et al., 2021).

The spread of COVID-19 has also been modelled within other facilities during electoral events with the main objective of avoiding queues at polling stations to reduce the risk of cluster formation associated with infections (Mondschein et al., 2022; Schmidt and Albert, 2022; Bernardo et al., 2022; Weibrecht et al., 2021). Another large-scale event, the religious pilgrimage of Muslims to Masjid-Al-Haram, also known as Hajj, was modelled by Tofighi et al. (2022) to simulate the dynamics of COVID-19 transmission under different conditions.

In another category of COVID-19 propagation studies using DES, authors have modelled control lanes or queues in public transportation to assess the impact of social distancing on their performance. In this context, several authors have modelled security control or boarding lanes at airports (Moreira et al., 2023; Zhu et al., 2022; Qureshi and

Qureshi, 2022; Kierzkowski and Kisiel, 2020) or queues at train stations (Zhu et al., 2023) or even in subway stations (Khattak et al., 2022).

The last category of studies aimed to propose a new simulation model to assess the impact of human mobility on the spread of infectious diseases, by simulating different scenarios of inter- and intra-city travel (Topîrceanu and Precup, 2021) or to evaluate the effectiveness of different interventions in pandemic management within cities (Angelopoulou and Mykoniatis, 2024; Setiawan et al., 2021). The objective was to analyse the impact of various COVID-19 control strategies on virus transmission.

4.2.2 Types of simulation

In modelling the systems studied for managing the spread of COVID-19, discrete-event simulation has often been combined with agent-based simulation (Angelopoulou and Mykoniatis, 2024; Possik et al., 2023; Zhu et al., 2023; Tofighi et al., 2021, 2022; Zhu et al., 2022; Qiu et al., 2021; Cimini et al., 2021). This method involves developing a hybrid simulation model composed of an agent-based simulation to simulate virus propagation and a discrete-event simulation model to simulate interactions between individuals in an indoor environment. This approach allows capturing specific behaviours of individuals and adapting them to different epidemiological conditions and types of modelled facilities.

4.2.3 Simulation objectives

The main objective of these studies was to model contacts between infected and non-infected citizens (Moreira et al., 2023; Tofighi et al., 2022; Zhu et al., 2022; Qiu et al., 2021), as well as between employees, healthcare providers, and citizens or patients (Possik et al., 2023; Mondschein et al., 2022; Tofighi et al., 2021). However, other measures were studied during these simulations. Among these measures are the system's capacities to handle patients (Allen et al., 2020), passenger flow control (Zhu et al., 2023), waiting time (Mondschein et al., 2022; Weibrecht et al., 2021; Schmidt and Albert, 2022), citizens' dwell time in facilities (Schmidt and Albert, 2022), boarding time (Moreira et al., 2023; Qureshi and Qureshi, 2022), the number of citizens present in facilities (Schmidt and Albert, 2022), and outpatient and hospital workload (Allen et al., 2020).

4.3 Mass vaccination

4.3.1 Simulated infrastructures

Various types of mass vaccination facilities have been addressed through simulation. These facilities can be categorised into two types: walk-in vaccination centres (Sala et al., 2023; Jerbi and Masmoudi, 2023; Asgary et al., 2022; Wang et al., 2022; Pilati et al., 2021) and drive-through vaccination centres (Asgary et al., 2020, 2021a, 2021b, 2022). The first type is the traditional one, where citizens move between stations in the centre on foot. The second is a more recent type that emerged with COVID-19 to limit contacts between citizens and between citizens and centre staff. In this type of centre, citizens arrive in their vehicles and remain there to move between centre stations. Unlike the first type, which can be held in any indoor facility such as gyms (Wang et al., 2022), a hockey stadium (Asgary et al., 2022), or a university sports centre (Sala et al., 2023), the second type of vaccination centre requires a large space, such as a parking lot (Asgary et al., 2020, 2022; Pilati et al., 2021), to manage the flow of a large number of cars.

All simulation studies, except for those by Asgary et al. (2020, 2022) reported real case studies. Four mass vaccination centre simulation studies were implemented in the American continent (USA and Canada); two were implemented in Europe (Italy), one in Africa (Tunisia), and another in Asia (China).

4.3.2 Simulation objectives

Although they all simulate mass vaccination centres, the objectives of these studies differ. Some studies aimed to design, operate, and evaluate the feasibility and effectiveness of mass vaccination centres (Asgary et al., 2020, 2021b). Sala et al.'s (2023) study, on the other hand, examined the evolution of certain performances of real mass vaccination centres, such as the maximum number of vaccinated patients and the main resource utilisation ratio. Some other studies aimed primarily to evaluate the effectiveness of managing a real mass vaccination centre in response to the variability of citizen arrivals through different arrival scenarios (Jerbi and Masmoudi, 2023; Asgary et al., 2022). Wang et al. (2022) aimed in their study to optimise personnel allocation in vaccination centres. The last category of studies aimed to develop models of real and imaginary mass vaccination centres, which were subsequently used to create a digital twin of these centres to map citizen flows in real-time (Pilati et al., 2021) or to develop a machine learning model of these centres to predict the outcomes of mass vaccination (Asgary et al., 2021a).

5 Conclusions

This study significantly advances our understanding of discrete event simulation as a pivotal operational research tool in addressing the multifaceted challenges presented by the COVID-19 pandemic. Through a comprehensive bibliometric analysis, we have demonstrated how DES has not only contributed to immediate responses but also laid the groundwork for future public health strategies. Key findings and their broader implications are:

- Impact on healthcare operations management: the findings reveal that DES has been instrumental in optimising healthcare operations, facilitating effective resource allocation, and enhancing the efficiency of public health systems. By modelling various scenarios, researchers have used DES to simulate healthcare workflows, helping decision makers implement strategies that minimise wait times and improve patient outcomes. This impact is crucial in the context of managing healthcare systems under stress, particularly during surges in patient volume associated with pandemic conditions.

- Contributions to virus propagation management: our analysis highlights DES's role in understanding and controlling virus spread. By analysing infection rates and the effects of various public health interventions, DES has provided valuable insights into how different strategies can influence the trajectory of the pandemic. This understanding is vital for developing future pandemic response plans, allowing health authorities to anticipate and mitigate outbreaks more effectively.
- Optimisation of mass vaccination operations: the significant attention given to mass vaccination operations underscores the urgent need for effective deployment strategies. DES has enabled researchers and public health officials to simulate vaccination logistics, ensuring that resources are utilised efficiently. The modelling of different vaccination scenarios has informed policy decisions, illustrating the critical role of DES in achieving high vaccination coverage and managing public health crises.
- Recognition of academic contributions: citation analysis indicates a robust engagement with DES in the academic community, revealing that a diverse range of authors from various disciplines, including operational research, healthcare management, and medical informatics, have contributed to the literature. This cross-disciplinary collaboration enhances the depth of research on DES applications, promoting innovative approaches to complex health challenges. The emerging prominence of newer authors reflects a dynamic field that continues to evolve in response to pressing public health needs.

While this study has focused on the contributions of DES during the COVID-19 pandemic, its applicability extends far beyond this context. Future research should explore the potential of DES in other relevant areas, such as:

- Post-pandemic strategies: investigating how DES can aid in safely reopening societies, evaluating the impact of interventions, and optimising resource distribution in the aftermath of a health crisis.
- Broader public health applications: applying DES to other pressing health issues, such as chronic disease management, emergency response planning, and healthcare accessibility.

By leveraging the insights gained from this study, future investigations can enhance our preparedness for subsequent health crises, ensuring that we utilise innovative methodologies like DES to inform evidence-based decision making.

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