Proceedings of the 2025 Winter Simulation Conference
E. Azar, A. Djanatliev, A. Harper, C. Kogler, V. Ramamohan, A. Anagnostou, and S. J. E. Taylor, eds.

MAPPING APPLICATIONS OF COMPUTER SIMULATION IN ORTHOPEDIC SERVICES: A TOPIC MODELING APPROACH

Alison Harper[1], Thomas Monks[2], Navonil Mustafee[1], Jonathan T. Evans [2,3], and Al-Amin Kassam[3]

[1]Centre for Simulation, Analytics, and Modelling, University of Exeter Business School, Exeter, UK
[2]The Medical School, University of Exeter, Exeter, UK
[3]Royal Devon University Hospital, Exeter, UK

ABSTRACT

Orthopedic services are characterized by high patient volumes, long elective waits, unpredictable emergency demand, and close coupling with other hospital processes. These present significant challenges in meeting operational targets while maintaining quality of care. In healthcare, simulation has been widely used for addressing such challenges. Topic modeling is used to identify and analyze academic papers using operational-level simulation for orthopedic service delivery. We analyzed 37 papers over twenty years, combining a structured analysis with topic modeling to categorize and map applications. Despite widespread recognition of its potential, simulation remains underutilized in orthopedics, with fragmented application and limited real-world implementation. Recent trends indicate a shift toward system-wide approaches that better align with operational realities and stakeholder needs. Future research should aim to bridge methodological innovation with collaboration and practical application, such as hybrid and real-time simulation approaches focusing on stakeholder needs, and integrating relevant operational performance metrics.

1 INTRODUCTION

1.1 Background

As healthcare systems grow in complexity, the need to streamline resource allocation, reduce costs, and retain a focus on patient outcomes is increasing. Coordinating operating theaters, beds, and surgical workflows in trauma and orthopedic departments is complicated by unpredictable emergency admissions, challenges in protecting elective beds and theaters, strict performance targets, and unique workflow characteristics such as post-operative care pathways (NICE 2023; Royal College of Physicians 2025; GIRFT 2020). Orthopedics has the UK's largest elective (non-urgent) surgery backlog, well below national standards for waiting time performance (NHS England 2025c). Patients waiting for scheduled elective procedures experience a clinically significant deterioration in health-related quality of life and joint-specific function (Scott et al. 2024), while canceled procedures are distressing for patients and their families, and disruptive and costly for healthcare systems (Caesar et al. 2021). In the UK, around 1% of scheduled surgical procedures are canceled at the last minute for non-clinical reasons, which include lack of beds and emergency (trauma) cases needing theater (NHS England 2025b).

These pressures are intensified by trauma orthopedics where emergency falls and hip fractures drive unpredictable demand, and patients are waiting longer for emergency admission (NHS England 2025a). With aging populations, falls are both increasingly prevalent and more likely to result in a hip fracture, one of the most significant consequences of falls among the elderly and a major public health issue. Each year around 70,000 people break their hip in the UK (Royal College of Physicians 2025), with a cost to acute services alone of around £1 billion per year (NICE 2023). The associated demand on health services is projected to more than double by 2060 (Murphy et al. 2024). These challenges for trauma and orthopedic services are not confined to the UK, but are observed more broadly in the international context (Caesar et al. 2021; Sawadogo et al. 2022; McCall et al. 2021; Denis et al. 2022).

1.2 Simulation in Trauma and Orthopedics

Similar challenges have driven the adoption of Operational Research (OR) methodologies across the healthcare domain, aiming to increase operational efficiency, reduce costs, and improve outcomes (Vázquez-Serrano et al. 2021; Roy et al. 2021; Ouda et al. 2023). In orthopedic care settings, a comprehensive review categorized OR publications (Howells et al. 2023). The authors particularly identified the need for further research in operational capacity planning and waiting list management; in patient flow, especially for time-related outcomes; and in hybrid applications. Simulation methods are particularly suited to all these areas. Discrete-event simulation (DES) has long been the dominant simulation methodology for modeling healthcare workflows due to its ability to capture sequential processes and stochastic variability (Roy et al. 2021). Its strength lies in its granular representation of time-dependent events, in particular patient flow through a network of services. Both hybrid simulation –combining two or more simulation methods– and hybrid modeling –combining simulation with techniques and methods from OR and other disciplines– aim to more completely model a problem situation than single methods (Kar et al. 2024; Vázquez-Serrano et al. 2021; Mustafee and Powell 2018). For example, healthcare systems exhibit macro and micro levels of complexity; are interdependent on other system components; and system performance is often driven by human behavior, for example, staff coordination failures can lead to delayed discharges (Kar et al. 2024).

1.3 Study Aims

This study aims to investigate how simulation has been used to support operational-level service planning in trauma and orthopedic services. The purpose of the study is to understand the current state-of-the-art, and to identify research gaps and opportunities to strengthen the implementation of simulation for orthopedic service planning. The specific aims are:

- To identify studies that have used simulation methods for evaluating orthopedic service delivery;
- To investigate methods, application areas, context of care, key performance indicators, and outcomes;
- To classify papers by topics, and map the application domain focusing on future opportunities.

2 METHODS

2.1 Search Strategy

SCOPUS and Web of Science (WoS) were searched for relevant journal articles and conference proceedings covering DES, agent-based simulation (ABS) or System Dynamics (SD) applied to operational-level orthopedic service delivery published between January 2004 and search date 8 February 2025. To capture operational-process terminology, an iterative set of keywords was derived from pilot searches and from two prior reviews on simulation for patient flow (Soh et al. 2017; Williams et al. 2021). PubMed was not searched because SCOPUS and WoS have near-complete coverage of the journals that publish simulation work; SCOPUS has previously demonstrated wide coverage for systematic reviews of modeling and simulation in healthcare (Jahangirian et al. 2011). Nevertheless, we acknowledge that this approach may have excluded a small number of clinically focused papers, which we note as a limitation. To mitigate this risk and broaden the search, we conducted forward and backward citation chasing using Spidercite (https://tera-tools.com/spidercite), applying the same inclusion and exclusion criteria to all additional records.

2.2 Selection Criteria and Data Extraction

SCOPUS and WoS datasets were combined and all duplicates were removed based on DOI using case normalization. The dataset was initially screened by abstract. Unless for service planning, papers that focused on cost-effectiveness, long-term burden of care, simulation for medical education, simulation of medical components, or hospital infrastructure were excluded. The remaining dataset underwent forward/backward citation chasing and de-duplication before being merged for full-text review. A final total of 37 papers were included for analysis. Our full search strings, inclusion/exclusion criteria, PRISMA compliant workflow, and all data and analysis for this paper, can be viewed at GitHub (PythonHealthDataScience 2025).

2.3 Analysis Framework

We use a structured full-text analysis combined with topic modeling to analyze and synthesize the literature. Topic modeling is an unsupervised machine learning technique that identifies underlying themes or topics in large text datasets by grouping related words and concepts (Sheng et al. 2023; Alhashmi et al. 2024). It was conducted to supplement the structured analysis by revealing latent themes and relationships within the literature and providing systematic triangulation with manual coding. Examining relationships between topics and the structured analysis can help identify emerging trends and gaps in the existing body of knowledge (Sheng et al. 2023). Given the small size of our dataset, the structured analysis enhances topic coherence and interpretability, while topic modeling adds a systematic and reproducible layer of abstraction that uncovers patterns and relationships in the literature with greater rigor than manual review alone.

2.3.1 Full Text Analysis

A full text manual analysis of papers extracted the following data: (i) Publication characteristics (e.g., type, year, authors, source), simulation software; (ii) Problem and application focus (emergency departments (ED), operating theaters, outpatient departments/clinics (OPD), inpatient wards), the context (elective/emergency); (iii) Methods used (simulation method/s, other), key performance indicators (KPIs) (patient satisfaction, efficiency, costs, resource utilization); (iv) Implementation status, defined in line with Moretto et al. (2019), as the intention, initial decision or initial action to implement findings in practice. This is an indication of the degree to which the study has informed, or is expected to inform, real-world improvement.

2.3.2 Topic Modeling

Topic modeling is used to study themes in textual data, and relies on a combination of computational clustering of co-occurring terms, and post-processing interpretation (Brookes and McEnery 2019). Topic modeling was performed using Latent Dirichlet Allocation (LDA), implemented via Gibbs sampling in R v4.4.2 (Jelodar et al. 2019). Text pre-processing involved converting documents from PDF to text format and standardizing spelling, removing punctuation, numbers, and whitespace, and lemmatizing words to reduce morphological variants (Brookes and McEnery 2019). An enhanced stopword list was created through two stages: a Term Frequency-Inverse Document Frequency (tf-idf) analysis to remove common words across documents (high-frequency, low-information terms, e.g., simulation, healthcare, research), complemented by manually identified domain-specific stopwords to further refine the text data (e.g., journal, author names, or uninformative words). The aim of this step was to maximize coherence of clustered topics.

A Document-Term Matrix (DTM) was generated and sparse terms were removed to focus analysis on relevant vocabulary. The number of topics (k=3) was selected based on interpretability and coherence scores. Due to the small dataset, a small number of topics was chosen. Typically k is chosen based on predictive performance on a hold-out set of documents (Alhashmi et al. 2024), however, our small corpus favors interpretability. Fewer topics can be more interpretable and easier to label, while more topics can fragment the dataset. Our dual approach using parallel manual coding aimed to overcome a weaknesses of topic modeling, which is meaningful cluster coherence (Brookes and McEnery 2019).

The LDA was executed with a fixed random seed for reproducibility. Internal evaluation measures the quality of the topics. Evaluation involved a combination of topic coherence, topic diversity, and word entropy per topic (Goyal and Kashyap 2023; Bernhard et al. 2023; Boyd-Graber et al. 2014). *Topic coherence* measures the semantic similarity of words within a topic; higher coherence indicates that the words are more related and meaningful. *Topic diversity* is the ratio of unique words to total words across topics. A high value (close to 1) indicates that the topics have minimal overlap in their word distributions. *Word entropy* measures the distribution of word probabilities within each topic. Higher entropy indicates that the topic has a more even distribution of words, meaning no single word dominates the topic. Topics were interpreted based on their most representative terms, and documents were assigned dominant topics for further analysis. This enabled examination of relationships between topics, simulation methods, and outcomes, providing additional context for the review. We externally evaluated our topics using a subset of

papers. The methodology is summarized in Figure 1, combining topic clusters and manually-coded study attributes to map the literature.

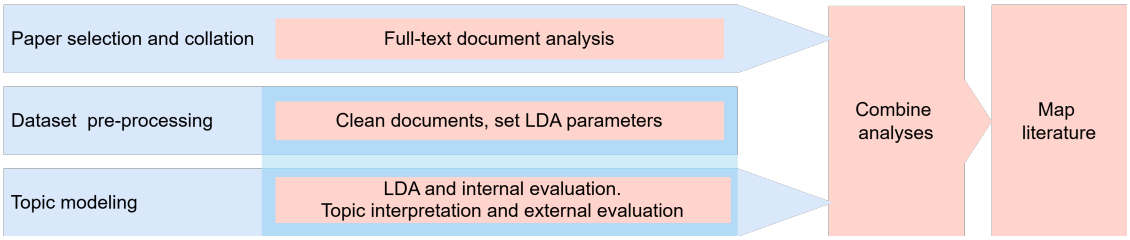

Figure 1: Analysis Framework.

3 RESULTS

3.1 Topics and Evaluation

Topic modeling was undertaken on the 37 papers to cluster overarching themes across the reviewed literature. The identified topics from the LDA analysis are distinguished by prominent terms and concepts: Topic 1 identified outpatient clinical scheduling and appointment management; Topic 2 primarily identified surgical scheduling and theater utilization; and Topic 3 focused on patient pathways, costs, and surgical processes. The interpretation involved examining the top 30 words per cluster alongside the papers. Figure 2 shows the ten dominant terms in each topic cluster. Table 1 lists the publications and the dominant topic within each. Where authors have been involved with multiple studies, they tend to be associated with the same topic cluster. The number of documents primarily associated with each topic was 16 for Topic 1, 9 for Topic 2, and 12 for Topic 3. Hence the majority of studies investigated outpatient clinic processes. We measured topic coherence, topic diversity, and word entropy to evaluate our method. Our initial coherence scores were relatively low, suggesting the topics may not be highly interpretable. Our diversity score was very high (0.97) indicating that topics had minimal overlap in their word distributions with distinct topics, and our entropy values were high, suggesting that the topics were balanced, and not dominated by a few words. To improve the balance between diversity and coherence, further domain-specific stopwords were removed from the top 30 terms of each topic to reduce noise. This improved the coherence scores across all topics, with a diversity score of 0.9, indicating slightly more word overlap per topic. Entropy remained stable, with balanced word distributions across all topics. Topics were manually inspected to confirm coherence.

3.2 Publication Profiling

Across a twenty-year time period, we identified a total of 37 journal (n=28) and conference papers (n=9) applying simulation to orthopedic services. The most notable aspect of this is the sparsity of research in this area, given the scale and bed-day consumption of the specialty (GIRFT 2020). Currently, around 100 papers applied to healthcare are published in journals, conferences and books each year using DES alone (Monks, Harper, and Mustafee 2024), so it is surprising that so few address orthopedics planning. All studies used DES. ARENA was the most commonly used software (n=12), followed by Simul8 (n=6) and AnyLogic (n=6). In four cases the software was unknown. Open source software was used in 4 papers (Java n=2; Python n=2). In two cases the code was made available. Hybrid approaches combined DES with ABS (n=3), SD (n=1) or non-simulation methods (n=6), such as multiple linear regression (Saadouli and Ltaif 2021) or optimization (Vahdat et al. 2019) (Table 2). Elective services are more commonly modeled than emergency processes; some papers, including all but two of those in Topic 2, looked at both. While the majority of papers modeled a single application area (Table 2), the papers that addressed emergency processes all modeled three or more application areas (Boyle and Mackay 2022; Dehlendorff et al. 2010; Dehlendorff et al. 2010; Johnson et al. 2016; Simwita and Helgheim 2016a; Simwita and Helgheim 2016b; Standfield et al. 2017; Standfield et al. 2016; Steins et al. 2010). Theaters and Outpatient departments

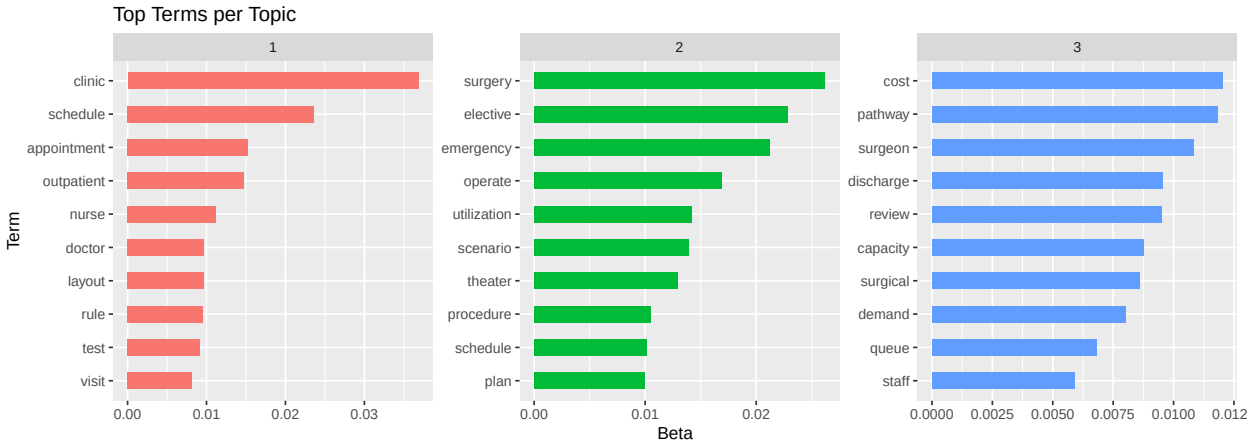

Figure 2: The ten top terms per topic. Beta values indicate the likelihood of each word within a probability distribution over words. **Topic 1** identifies outpatient clinical scheduling and appointment management; **Topic 2** primarily identifies surgical scheduling and theater utilization; **Topic 3** focuses on surgical pathways, costs, and patient processes.

Table 1: Publications included for analysis, and dominant topic associated with each paper.

Publication	**Topic**	**Publication**	**Topic**
[1] Anderson et al. (2017)	3	[19] Montgomery et al. (2013)	1
[2] Baril et al. (2014)	1	[20] Moretto et al. (2019)	3
[3] Bowers and Mould (2004)	2	[21] Persson et al. (2017)	2
[4] Boyle and Mackay (2022)	3	[22] Persson and Persson (2010)	2
[5] Chen et al. (2010)	1	[23] Pu et al. (2024)	2
[6] Comans et al. (2017)	3	[24] Rachuba et al. (2018)	3
[7] Dehlendorff et al. (2010)	2	[25] Reece et al. (2021)	1
[8] Dehlendorff et al. (2010)	2	[26] Rohleder et al. (2011)	1
[9] Ferrand et al. (2014)	2	[27] Saadouli and Ltaif (2021)	1
[10] Harper et al. (2023)	3	[28] Simwita and Helgheim (2016a)	3
[11] Harper et al. (2023)	3	[29] Simwita and Helgheim (2016b)	3
[12] He et al. (2013)	1	[30] Standfield et al. (2016)	3
[13] Johnson et al. (2016)	1	[31] Standfield et al. (2017)	3
[14] Kittipittayakorn and Ying (2016)	1	[32] Steins et al. (2010)	2
[15] Komashie et al. (2008)	2	[33] Suhaimi et al. (2018)	1
[16] Ltaif et al. (2023)	1	[34] Vahdat et al. (2017)	1
[17] Lu et al. (2013)	1	[35] Vahdat et al. (2019)	1
[18] Lu et al. (2014)	1	[36] Van Der Meer et al. (2005)	3
		[37] Weerawat et al. (2013)	1

(OPD) are the most frequently modeled application areas, with ED and wards the least frequent (Table 2). Of those who modeled wards, all focused on elective services only (Harper et al. 2023; Harper et al. 2023; Reece et al. 2021). Those who modeled ED included X-ray but did not look at downstream processes (Rachuba et al. 2018; Montgomery et al. 2013). Process efficiency and resource utilization are the most commonly reported metrics (Table 2). Those who measured costs are predominantly associated with Topic 3, and three of the five modeled three or more application areas (Standfield et al. 2017; Standfield et al. 2016; Moretto et al. 2019).

Only seven papers reported an intention or initial decision to implement real-world change based on the modeling results. This aligns with previous reviews of simulation in healthcare (Roy et al. 2021). Of those, all except one focused only on elective services (Harper et al. 2023; Harper et al. 2023; Moretto et al. 2019; Reece et al. 2021; Rohleder et al. 2011; Van Der Meer et al. 2005). All are predominantly Topic 3 apart from two which are more associated with Topic 1.

Table 2: Combined summary of hybrid methods ('Other' refers to any non-simulation method. All studies used DES), application areas, departments, and KPI metrics reported across studies.

Category	Study Numbers
Hybrid methods reported	
DES + ABS	6, 14, 18
DES + SD	12
DES + Other	16, 22, 27, 30, 31, 35
Number of application areas	
One Application Area	2, 3, 5, 9, 10, 11, 12, 14, 15, 17, 18, 21, 22, 23, 33, 34, 35, 36
Two Application Areas	1, 16, 19, 24, 25, 26, 27, 37
Three Application Areas	4, 6, 7, 8, 13, 20, 28, 29, 30, 31, 32
Specific application areas	
Emergency Department	19, 24
Theaters	3, 4, 6, 7, 8, 9, 15, 21, 22, 23, 28, 29, 30, 31, 32
OPD/Clinics	1, 2, 4, 5, 6, 12, 13, 14, 16, 17, 18, 20, 26, 27, 28, 29, 30, 31, 33, 34, 35, 36, 37
Wards	10, 11, 25
KPI metrics	
Patient Satisfaction	14, 16, 17
Process Efficiency	2, 4, 5, 7, 8, 9, 10, 11, 12, 13, 14, 16, 17, 18, 19, 21, 22, 24, 26, 27, 28, 29, 31, 32, 33, 34, 35, 36, 37
Costs	1, 20, 22, 30, 31
Resource Utilization	1, 2, 3, 4, 6, 7, 9, 10, 11, 12, 13, 15, 19, 20, 21, 22, 23, 24, 25, 28, 29, 31, 32, 34, 36, 37

3.3 Temporal Analysis

Figure 3 shows the distribution of publications by document type and by topic per year. Most papers are published in journals. There is temporal progression from Topics 2 to 1 to 3, showing that interest in simulation topics has evolved over time. The median year for Topic 2 is 2010, for Topic 1 is 2015, and for Topic 3 is 2017. This indicates a potential shift away from isolated problem areas, such as operating theater scheduling, toward more integrated, pathway-level planning approaches.

3.4 Relationships Between Topics and Features

The alluvial plot in Figure 4 maps the relationships between research topics, reported application areas (ED, OPD, Theatres, Wards), and reported implementation of results. The flows highlight clear distinctions between topic clusters. Topic 2 is exclusively associated with Theatres, whereas Topic 1 is concentrated in OPD, and Topic 3 spans all application areas. This pattern reinforces our earlier interpretation of topic clusters as distinct in both scope and focus.

Implementation patterns vary markedly across topics. No papers in Topic 2 reported an intention or initial decision to implement, which may reflect different methodological challenges. Topic 1 shows limited implementation activity, confined to OPD and Wards. In contrast, the majority of implementation reports come from Topic 3, with coverage across all departments. This may reflect Topic 3's broader applicability, greater operational flexibility, or — as suggested by the temporal trend in Figure 3 — a more recent surge in interest in translating research into practice.

Figure 5 shows both the Key Performance Indicators (KPIs) per topic: *Patient Satisfaction, Costs, Efficiency, and Resource Utilisation*; and the methods used per topic. Unsurprisingly, process efficiency and resource utilisation were the KPIs most commonly addressed across all papers. Topic 2, focusing on operating theater scheduling, primarily measured resource utilization and efficiency. Topic 1, focused

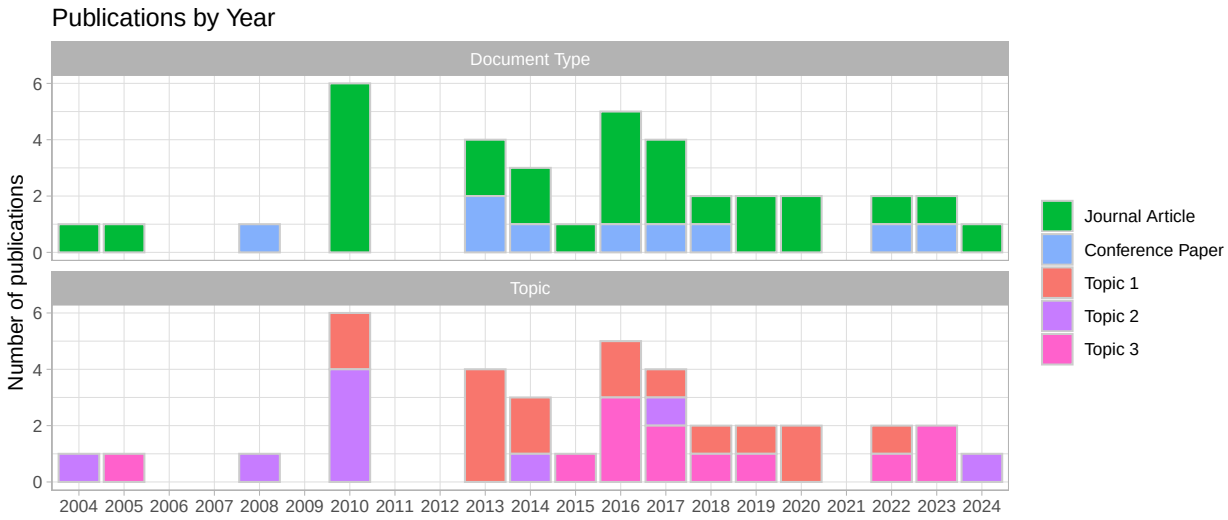

Figure 3: Publication type and topic by year.

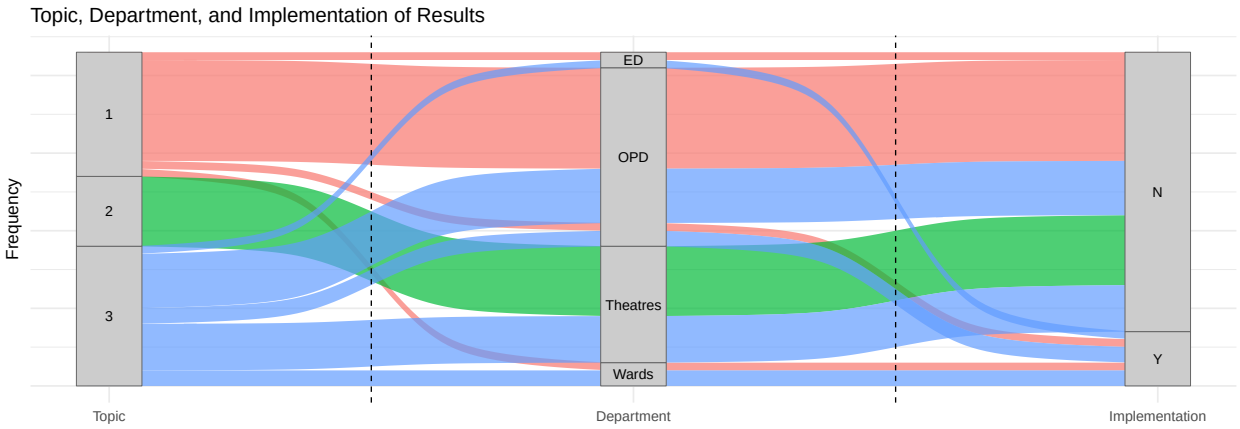

Figure 4: Alluvial plot showing the relationship between the dominant topic associated with each paper, and application area and project outcome (in terms of results implementation) as reported in the papers.

on outpatient clinics and scheduling appointments, was primarily concerned with efficiency, but papers in this topic also measured patient satisfaction. Generally, wait times were used as a proxy for satisfaction (Kittipittayakorn and Ying 2016; Lu et al. 2013), while Ltaif et al. (2023) used goal programming derived from wait times for a specific satisfaction outcome. Chen et al. (2010), Rohleder et al. (2011), Vahdat et al. (2019) all mentioned wait times and efficiency as drivers of patient satisfaction. Topic 3, focusing on surgical pathways and discharge planning, primarily investigated resource utilization, efficiency and costs. No studies investigated health outcomes or integrated specific operational targets into the simulation model.

DES dominates the methods used, which is not unexpected for operational-level modeling. A minority of hybrid methods were employed across all topics. Lu et al. (2014) and Kittipittayakorn and Ying (2016) (both Topic 1) used hybrid DES-ABM to incorporate staff autonomous, adaptive behavior, both focusing on reducing OPD wait times, while Comans et al. (2017) modeled individual characteristics of patients across multiple departments (Topic 3). Simulation-optimization frameworks allowed scenario testing under uncertainty. Standfield et al. (2016) and Standfield et al. (2017), both Topic 3, demonstrated that DES with dynamic queuing more accurately captures capacity constraints and real-world queuing dynamics

than traditional methods for evaluating cost-effectiveness and resource allocation. Persson and Persson (2010) used optimization policies to evaluate theater performance, balancing cancellation, waiting times, and throughput (Topic 2). He et al. (2013) used a genetic algorithm to test OPD overbooking strategies (Topic 1). Saadouli and Ltaif (2021) used multiple linear regression to analyse how staffing levels impact patient flow through OPD clinics (Topic 1).

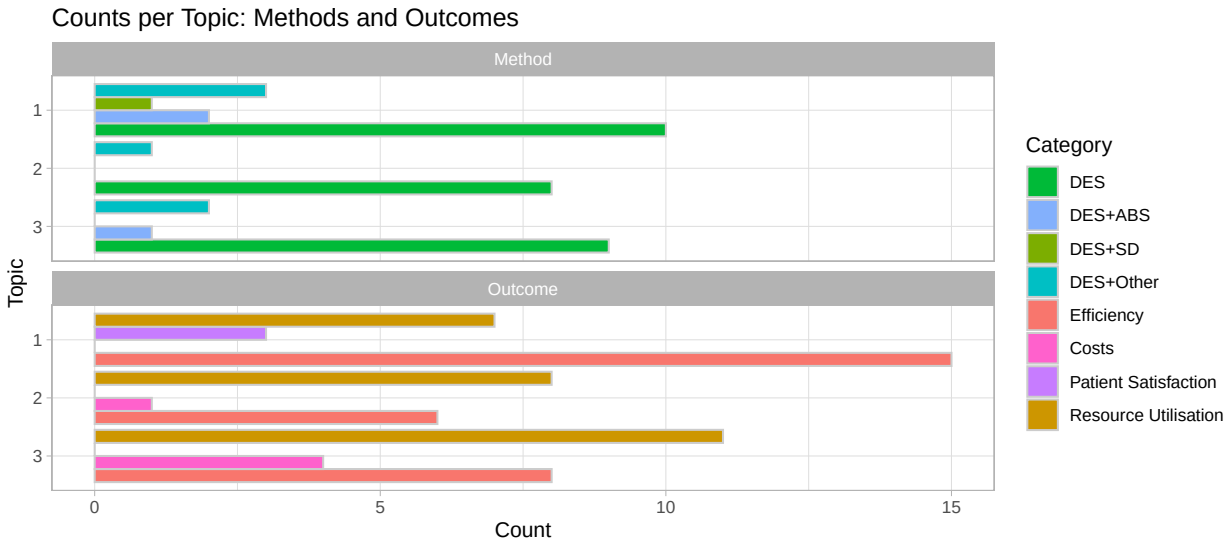

Figure 5: Methods used and Key Performance indicators per topic.

4 DISCUSSION

This scoping review highlights the underutilization of simulation in trauma and orthopedic service planning, with 37 relevant studies over two decades. As the largest elective surgical specialty in the UK, and despite well-documented challenges—such as long elective waits, high emergency demand, and complex care pathways—simulation has been applied in a relatively narrow and fragmented way. Topic modeling identified three main clusters: (1) outpatient clinic management, (2) surgical scheduling and theater utilization, and (3) broader pathway and cost-related planning. Most studies focused on outpatient efficiency (Topic 1), while surgical scheduling (Topic 2)—a known operational bottleneck—was least represented and showed no evidence of real-world implementation. In contrast, Topic 3 studies demonstrated a shift toward whole-system modeling and were more likely to report implementation, suggesting these broader approaches are more aligned with real-world needs.

All studies used DES. Of the ten papers that used a hybrid approach, none planned or reported implementation, indicating that the focus is methodological or proof-of-concept, in contrast to the widely described aims of hybrid approaches (Kar et al. 2024; Mustafee and Powell 2018). Like most DES studies, KPIs centered on efficiency and resource utilization. However while these tended to measure 'wait times', no papers looked at specific orthopedic KPIs (Royal College of Physicians 2025), which in the UK are mandatory to report, such as <36 hours from arrival to surgery for hip fractures. Some papers investigated costs (Anderson et al. 2017; Moretto et al. 2019; Persson and Persson 2010; Standfield et al. 2016; Standfield et al. 2017). Patient wait times, notably in OPD models, were used as a proxy for patient satisfaction; Lu et al. (2013) and Lu et al. (2014) cited previous questionnaire research which evidenced this relationship in OPD. No papers looked at patient outcomes.

In line with previous reviews of simulation in healthcare (Roy et al. 2021), very few studies reported actual or intended implementation, reflecting a persistent gap between research and practice. Nonetheless, Topic 3 papers are both more recent, and more likely to be implemented. Of these, several explicitly described stakeholder engagement activities (Moretto et al. 2019; Van Der Meer et al. 2005; Harper et al.

2023) and model usability and/or reusability (Boyle and Mackay 2022; Harper et al. 2023; Van Der Meer et al. 2005). Two papers adhered to open standards by making their model code available. These have all been positively associated with model implementation (Harper et al. 2022).

Given the low engagement with orthopedics by the M&S community, there is enormous scope to contribute to addressing current pressing issues. Hybrid approaches have not yet seen the benefit they aim to achieve. For example, ABS can model patient or staff specific roles and behavior, without assuming deterministic behavior, and can lead to models that better represent reality (Comans et al. 2017; Lu et al. 2014; Kittipittayakorn and Ying 2016), yet there is no recent engagement with this approach. The complexity of orthopedic care pathways, their close coupling with other specialties at all stages of the surgical journey, and the need to accommodate both emergency and elective patient cohorts present opportunities for hybrid methods. While research has been done in this area, none of these papers are recent, or show evidence of informing practice. Incorporating both emergency and elective care presents a potential application area for real-time simulation research, where short-term planning models can be updated with the current system state of emergency patients. In healthcare, real-time simulation or digital twin research is still mainly at the conceptual stage, but orthopedic service delivery is a strong candidate for research in this area, with the potential to significantly improve operational responsiveness and patient outcomes. Finally, a further opportunity is the need for health services to work to operational performance measures (Royal College of Physicians 2025). In the UK, the National Hip Fracture Database (NHFD) specifies mandatory KPIs such as surgery within 36 hours of arrival, prompt orthogeriatric assessment, and early mobilisation. These measures are closely linked to patient outcomes, including reduced mortality, shorter length of stay, and improved functional recovery. Integrating such KPIs directly into simulation models would enable them to serve not only as tools for process efficiency, but also as decision-support systems that assess compliance with national standards, aligning modelling outputs with the priorities of clinicians, managers, and commissioners.

One limitation of our study is that we did not search PubMed, potentially excluding applications published in healthcare journals. Secondly, our specific search strings aimed to precisely capture relevant studies but may have inadvertently excluded relevant research employing different terminology. However, the use of forward and backward citation chasing mitigates both of these risks. Topic modeling is commonly used for large volumes of documents to identify 'hidden' topics present in the corpus, by algorithmically identifying underlying themes. As we identified a relatively small number of documents, caution about over-interpreting topics is needed. To mitigate this, we conducted both internal and external validation and tuned the model using a dual approach that combined statistical term relevance and manual inspection to identify and exclude irrelevant terms (stopwords). A strength of using a smaller set of documents is that we were able to map the topics with features derived from full-text reading. This validated topic interpretation, and enabled identification and mapping of both current approaches and promising avenues for future simulation research and practice in orthopedic service planning.

5 ACKNOWLEDGEMENTS

This work is supported by the National Institute for Health and Care Research (NIHR) Applied Research Collaboration South West Peninsula (T.M.) and NIHR Exeter Biomedical Research Centre (BRC) (J.T.E. & A.K.). The views expressed in this publication are those of the author(s) and not necessarily those of the NIHR or the Department of Health and Social Care. This work has been supported by the LEAP Digital Health Hub, which has been funded by EPSRC under grant number EP/X031349/1.

REFERENCES

Alhashmi, S. M., I. A. T. Hashem, and I. Al-Qudah. 2024. "Artificial Intelligence Applications in Healthcare: a Bibliometric and Topic Model-based Analysis". *Intelligent Systems with Applications* 21:200299.

Anderson, G. H., P. J. Jenkins, D. A. McDonald, R. Van Der Meer, A. Morton, M. Nugent *et al.* 2017. "Cost Comparison of Orthopaedic Fracture Pathways Using Discrete Event Simulation in a glasgow Hospital". *BMJ Open* 7(9):e014509.

Baril, C., V. Gascon, and S. Cartier. 2014. "Design and Analysis of an Outpatient Orthopaedic Clinic Performance with Discrete Event Simulation and Design of Experiments". *Computers & Industrial Engineering* 78:285–298.

Bernhard, J., M. Teuffenbach, and H. G. Boomgaarden. 2023. "Topic Model Validation Methods and Their Impact on Model Selection and Evaluation". *Computational Communication Research* 5(1):1–26.

Bowers, J., and G. Mould. 2004. "Managing Uncertainty in Orthopaedic Trauma Theatres". *European Journal of Operational Research* 154(3):599–608.

Boyd-Graber, J., D. Mimno, and D. Newman. 2014. *Care and Feeding of Topic Models: Problems, Diagnostics, and Improvements*, Volume 1st ed. CRC Press: Boca Raton.

Boyle, L., and M. Mackay. 2022. "A Reusable Discrete Event Simulation Model for Improving Orthopedic Waiting Lists". In *2022 Winter Simulation Conference (WSC)*, 973–984 https://doi.org/https://doi.org/10.1109/WSC57314.2022.10015512.

Brookes, G., and T. McEnery. 2019. "The Utility of Topic Modelling for Discourse Studies: a Critical Evaluation". *Discourse Studies* 21(1):3–21.

Caesar, U., L. Karlsson, E. Hamrin Senorski, J. Karlsson, and E. Hansson-Olofsson. 2021. "Delayed and Cancelled Orthopaedic Surgery; Are There Solutions to Reduce the Complex Set of Problems? a Systematic Literature Review". *International Journal of Clinical Practice* 75(9):e14092.

Chen, B., E. Li, Y. Kazunobu, K. Ken, N. Shinji, and W. Miao. 2010. "Impact of Adjustment Measures on Reducing Outpatient Waiting Time in a Community Hospital: Application of a Computer Simulation". *Chinese Medical Journal* 123:574–580.

Comans, T., A. Chang, L. Standfield, D. Knowles, S. O'Leary, and M. Raymer. 2017. "The Development and Practical Application of a Simulation Model to Inform Musculoskeletal Service Delivery in an australian Public Health Service". *Operations Research for Health Care* 15:13–18.

Dehlendorff, C., M. Kulahci, and K. K. Andersen. 2010. "Analysis of Computer Experiments with Multiple Noise Sources". *Quality and Reliability Engineering International* 26(2):137–146.

Dehlendorff, C., M. Kulahci, S. Merser, and K. K. Andersen. 2010. "Conditional Value at Risk as a Measure for Waiting time in Simulations of Hospital Units". *Quality Technology & Quantitative Management* 7(3):321–336.

Denis, A., J. Montreuil, E. J. Harvey, G. K. Berry, R. Reindl, and M. Bernstein. 2022. "Cancellations and Delays of Emergent Orthopedic Operations at a Canadian Level 1 Trauma Centre". *Canadian Journal of Surgery* 65(3):E382.

Ferrand, Y. B., M. J. Magazine, and U. S. Rao. 2014. "Partially Flexible Operating Rooms for Elective and Emergency Surgeries". *Decision Sciences* 45(5):819–847.

GIRFT 2020. "Getting It Right First Time: Orthopaedics: Follow-up Report". https://gettingitrightfirsttime.co.uk/wp-content/uploads/2020/02/GIRFT-orthopaedics-follow-up-report-February-2020.pdf. Accessed 26th February 2025.

Goyal, A., and I. Kashyap. 2023. "Comprehensive Analysis of Topic Models for Short and Long Text Data". *International Journal of Advanced Computer Science & Applications* 14(12):249–259.

Harper, A., T. Monks, R. Wilson, M. T. Redaniel, E. Eyles, T. Jones, *et al*. 2023. "Development and Application of Simulation Modelling for Orthopaedic Elective Resource Planning in England". *BMJ Open* 13(12):e076221.

Harper, A., N. Mustafee, and M. Yearworth. 2022. "The Issue of Trust and Implementation of Results in Healthcare Modeling and Simulation Studies". In *2022 winter simulation conference (WSC)*, 1104–1115 https://doi.org/10.1109/WSC57314.2022.10015276.

Harper, A., M. Pitt, and T. Monks. 2023. "Open-source Modeling for Orthopedic Elective Capacity Planning Using Discrete-event Simulation". In *2023 Winter Simulation Conference (WSC)*, 1077–1087 https://doi.org/10.1109/WSC60868.2023.10408227.

He, Y., M. Li, S. Sala-Diakanda, J. Sepulveda, A. Bozorgi, and W. Karwowski. 2013. "A Hybrid Modeling and Simulation Methodology for Formulating Overbooking Policies". In *IIE Annual Conference and Expo 2013*. October 28-30th, Orlando, Florida, 1358-1366.

Howells, M., P. Harper, G. Palmer, and D. Gartner. 2023. "Fractured Systems: a Literature Review of or/ms Methods Applied to Orthopaedic Care Settings and Treatments.". *Health Systems* 13:151–176.

Jahangirian, M., T. Eldabi, L. Garg, G. T. Jun, A. Naseer, B. Patel, *et al*. 2011. "A Rapid Review Method for Extremely Large Corpora of Literature: Applications to the Domains of Modelling, Simulation, and Management". *International Journal of Information Management* 31(3):234–243.

Jelodar, H., Y. Wang, C. Yuan, X. Feng, X. Jiang, Y. Li *et al*. 2019. "Latent Dirichlet Allocation (lda) and Topic Modeling: Models, Applications, a Survey". *Multimedia Tools and Applications* 78:15169–15211.

Johnson, G., J. Kiernan, A. Swan, E. Botwick, W. Spier, K. P. White, *et al*. 2016. "Designing Patient Throughput and Task Management Innovations in Orthopaedics". In *2016 IEEE Systems and Information Engineering Design Symposium (SIEDS)*: IEEE. 29th April, Charlottesville, USA, 124-129.

Kar, E., M. Fakhimi, C. Turner, and T. Eldabi. 2024. "Hybrid Simulation in Healthcare: a Systematic Exploration of Models, Applications, and Emerging Trends". *Journal of Simulation*:1–19.

Kittipittayakorn, C., and K.-C. Ying. 2016. "Using the Integration of Discrete Event and Agent-based Simulation to Enhance Outpatient Service Quality in an Orthopedic Department". *Journal of Healthcare Engineering* 2016(1):1–8.

Komashie, A., A. Mousavi, and J. Gore. 2008. "Using Discrete Event Simulation (DES) to Manage Theatre Operations in Healthcare: An Audit-based Case Study". In *Tenth International Conference on Computer Modeling and Simulation (uksim 2008)*: IEEE. 1-3rd April, Cambridge, UK, 360-365.

Ltaif, A., A. Ammar, and L. Khrifch. 2023. "A Goal Programming Approach Based on Simulation and Optimization to Serve Patients in an External Orthopedic Department". *Journal of Simulation* 17(4):509–519.

Lu, T.-P., J.-T. Shih, C. Kittipittayakorn, and G.-F. Lian. 2013. "Improving Outpatient Service Quality in Department of Orthopedic Surgery by Using Collaborative Approaches". In *Proceedings of the 2013 IEEE 17th International Conference on Computer Supported Cooperative Work in Design (CSCWD)*: IEEE. 27-29th June, Whistler, Canada, 515–520.

Lu, T.-P., P.-F. Tsai, and Y.-C. Chu. 2014. "An Agent-based Collaborative Model for Orthopedic Outpatient Scheduling". In *Proceedings of the 2014 IEEE 18th International Conference on Computer Supported Cooperative Work in Design (CSCWD)*: IEEE. 21-23th May, Hsinchu, Taiwan, 621-626.

McCall, M., M. Peebles, and N. A. Sandiford. 2021. "Cancellation of Elective Orthopaedic Procedures Is Not a Benign Practice and Is Often Preventable". *NZ Med J* 134:70–8.

Monks, T., A. Harper, and N. Mustafee. 2024. "Towards Sharing Tools and Artefacts for Reusable Simulations in Healthcare". *Journal of Simulation*:1–20 https://doi.org/doi.org/10.1080/17477778.2024.2347882.

Montgomery, J. B., B. A. Linville, and A. D. Slonim. 2013. "Desktop Microsimulation: A Tool to Improve Efficiency in the Medical Office Practice". *Journal for Healthcare Quality* 35(1):50–59.

Moretto, N., T. A. Comans, A. T. Chang, S. P. O'Leary, S. Osborne, H. E. Carter, *et al*. 2019. "Implementation of Simulation Modelling to Improve Service Planning in Specialist Orthopaedic and Neurosurgical Outpatient Services". *Implementation Science* 14:1–11.

Murphy, T., D. J. Culliford, S. Hawley, A. Johansen, M. R. Whitehouse, A. Judge *et al*. 2024. "Hip Fracture Projections up to the Year 2060: an Analysis Based on Data From the National Hip Fracture Database (NHFD) for England, Wales, and Northern Ireland". *Injury* 55(11):111863.

Mustafee, N., and J. H. Powell. 2018. "From Hybrid Simulation to Hybrid Systems Modelling". In *Proceedings of the 2018 Winter Simulation Conference*, 1430–1439 https://doi.org/10.1360/zd-2013-43-6-1064.

NHS England 2025a. "A&E Attendances and Emergency Admissions". https://www.england.nhs.uk/statistics/statistical-work-areas/ae-waiting-times-and-activity/. Accessed 25th February 2025.

NHS England 2025b. "Cancelled Elective Operations". https://www.england.nhs.uk/statistics/statistical-work-areas/cancelled-elective-operations/. Accessed 25th February 2025.

NHS England 2025c. "Referral to Treatment (rtt) Waiting Times". https://www.england.nhs.uk/statistics/statistical-work-areas/rtt-waiting-times/. Accessed 25th February 2025.

NICE 2023. "Hip Fracture: Management. National Institute for Health and Care Excellence". https://www.nice.org.uk/guidance/cg124/chapter/Recommendations. Accessed 26th February 2025.

Ouda, E., A. Sleptchenko, and M. C. E. Simsekler. 2023. "Comprehensive Review and Future Research Agenda on Discrete-event Simulation and Agent-based Simulation of Emergency Departments". *Simulation Modelling Practice and Theory* 129:102823.

Persson, M., H. Hvitfeldt-Forsberg, M. Unbeck, O. G. Sköldenberg, A. Stark, P. Kelly-Pettersson *et al*. 2017. "Operational Strategies to Manage Non-elective Orthopaedic Surgical Flows: a Simulation Modelling Study". *BMJ Open* 7(4):e013303.

Persson, M. J., and J. A. Persson. 2010. "Analysing Management Policies for Operating Room Planning Using Simulation". *Health Care Management Science* 13(2):182–191.

Pu, Z., S. Wu, and Y. Han. 2024. "A Discrete-event Simulation Model for Assessing Operating Room Efficiency of Thoracic, Gastrointestinal, and Orthopedic Surgeries". *World Journal of Surgery* 48(5):1102–1110.

PythonHealthDataScience 2025. "GitHub: scope_wsc_2025". https://github.com/pythonhealthdatascience/scope_wsc_2025.

Rachuba, S., K. Knapp, L. Ashton, and M. Pitt. 2018. "Streamlining Pathways for Minor Injuries in Emergency Departments Through Radiographer-led Discharge". *Operations Research for Health Care* 19:44–56.

Reece, K., J. Avansino, M. Brumm, L. Martin, and T. E. Day. 2021. "Determining Future Capacity for an Ambulatory Surgical Center with Discrete Event Simulation". *International Journal of Healthcare Management* 14(3):920–925.

Rohleder, T. R., P. Lewkonia, D. P. Bischak, P. Duffy, and R. Hendijani. 2011. "Using Simulation Modeling to Improve Patient Flow at an Outpatient Orthopedic Clinic". *Health Care Management Science* 14(2):135–145.

Roy, S., S. Venkatesan, and M. Goh. 2021. "Healthcare Services: a Systematic Review of Patient-centric Logistics Issues Using Simulation". *Journal of the Operational Research Society* 72(10):2342–2364.

Royal College of Physicians 2025. "National Hip Fracture Database: National Falls and Fragility Fracture Audit Programme (FFFAP)". https://www.nhfd.co.uk/. Accessed 25th February 2025.

Saadouli, H., and A. Ltaif. 2021. "Evaluating the Impact of Human Resource Management on the Patient Flow at an Outpatient Orthopedic Clinic". *International Journal of Healthcare Management* 14(4):1492–1500.

Sawadogo, M., A. S. Korsaga, S. Tinto, A. Ouedraogo, D. Denne, C. Darga, *et al*. 2022. "Factors for Postponement or Cancellation of Operating Programs Set in the Orthopedics-traumatology Department of Yalgado Ouédraogo University Teaching Hospital in Ouagadougou (Burkina Faso)". *Open Journal of Orthopedics* 12(12):451–462.

Scott, C. E., L. Z. Yapp, D. J. MacDonald, C. R. Howie, and N. D. Clement. 2024. "Patient Health-related Quality of Life Deteriorates Significantly While Waiting Six to 12 Months for Total Hip or Knee Arthroplasty: a Prospective Longitudinal Study". *The Bone & Joint Journal* 106(2):166–173.

Sheng, B., Z. Wang, Y. Qiao, S. Q. Xie, J. Tao, and C. Duan. 2023. "Detecting Latent Topics and Trends of Digital Twins in Healthcare: a Structural Topic Model-based Systematic Review". *Digital Health* 9:20552076231203672.

Simwita, Y., and B. Helgheim. 2016a. "Improving Surgeon Utilization in an Orthopedic Department Using Simulation Modeling". *Journal of Healthcare Leadership* Volume 8:41–50.

Simwita, Y., and B. Helgheim. 2016b. "Simulation Analysis of Resource Flexibility on Healthcare Processes". *Journal of Multidisciplinary Healthcare* Volume 9:519–528.

Soh, K. W., C. Walker, and M. O'Sullivan. 2017. "A Literature Review on Validated Simulations of the Surgical Services". *Journal of medical systems* 41:1–11.

Standfield, L., T. Comans, M. Raymer, S. O'Leary, N. Moretto, and P. Scuffham. 2016. "The Efficiency of Increasing the Capacity of Physiotherapy Screening Clinics or Traditional Medical Services to Address Unmet Demand in Orthopaedic Outpatients". *Applied Health Economics and Health Policy* 14(4):479–491.

Standfield, L. B., T. A. Comans, and P. Scuffham. 2017. "An Empirical Comparison of Markov Cohort Modeling and Discrete Event Simulation in a Capacity-constrained Health Care Setting". *The European Journal of Health Economics* 18(1):33–47.

Steins, K., F. Persson, and M. Holmer. 2010. "Increasing Utilization in a Hospital Operating Department Using Simulation Modeling". *SIMULATION* 86(8-9):463–480.

Suhaimi, N., V. Vahdat, and J. Griffin. 2018. "Building a Flexible Simulation Model for Modeling Multiple Outpatient Orthopedic Clinics". In *2018 Winter Simulation Conference (WSC)*, 2612–2623 https://doi.org/10.1109/WSC.2018.8632451.

Vahdat, V., J. Griffin, S. Burns, and R. Azghandi. 2017. "Proactive Patient Flow Redesign for Integration of Multiple Outpatient Clinics". In *2017 Winter Simulation Conference (WSC)*, 2893–2904 https://doi.org/https://doi.org/10.1109/WSC.2017.8248012.

Vahdat, V., A. Namin, R. Azghandi, and J. Griffin. 2019. "Improving Patient Timeliness of Care Through Efficient Outpatient Clinic Layout Design Using Data-driven Simulation and Optimisation". *Health Systems* 8(3):162–183.

Van Der Meer, R. B., L. A. Rymaszewski, H. Findlay, and J. Curran. 2005. "Using OR to Support the Development of an Integrated Musculo-skeletal Service". *Journal of the Operational Research Society* 56(2):162–172.

Vázquez-Serrano, J., R. Peimbert-García, and L. Cárdenas-Barrón. 2021. "Discrete-event Simulation Modeling in Healthcare: A Comprehensive Review". *International Journal of Environmental Research and Public Health* 18:12262.

Weerawat, W., J. Pichitlamken, and P. Subsombat. 2013. "A Generic Discrete-event Simulation Model for Outpatient Clinics in a Large Public Hospital". *Journal of Healthcare Engineering* 4(2):285–305.

Williams, E., D. Gartner, and P. Harper. 2021. "A Survey of OR/MS Models on Care Planning for Frail and Elderly Patients". *Operations Research for Health Care* 31:100325.

AUTHOR BIOGRAPHIES

ALISON HARPER is a Lecturer in Operations and Analtyics at University of Exeter Business School. Her research interests include applied health and care research, reusable simulation models, real-time discrete-event simulation, and hybrid modeling. Her email address is a.l.harper@exeter.ac.uk.

THOMAS MONKS is an Associate Professor of Health Data Science at University of Exeter Medical School. His research interests include open science for computer simulation, urgent and emergency care, and real-time discrete-event simulation. His email address is t.m.w.monks@exeter.ac.uk.

NAVONIL MUSTAFEE is a Professor of Analytics and Operations Management at the University of Exeter Business School, UK. His research focuses on M&S methodologies and Hybrid Modelling and their application in healthcare, supply chain management, circular economy and resilience and adaptation due to climate change. He is a Joint Editor-in-Chief of the Journal of Simulation (UK OR Society journal). His e-mail address is n.mustafee@exeter.ac.uk.

JONATHAN T. EVANS is a Clinical Senior Lecturer in Trauma & Orthopaedics and Consultant Hip Surgeon at the University of Exeter and the Exeter Hip Unit. He is part of the data analysis team for the National Joint Registry at the University of Bristol and a Clinical Fellow of the National Hip Fracture Database, focusing on periprosthetic femoral fractures and environmental impact assessments in surgical research. His e-mail address is j.t.evans@exeter.ac.uk.

AL-AMIN KASSAM is a Consultant Orthopaedic Surgeon in Exeter and co-clinical lead of the South West Ambulatory Orthopaedic Centre (SWAOC). He has completed specialist fellowships at the Nuffield Orthopaedic Centre in Oxford and the Exeter Hip Unit. He specialises in complex primary and revision hip arthroplasty and has a special interest in medical leadership. His e-mail address is al-amin.kassam@nhs.net.