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A structured literature review of simulation modelling applied to Emergency Departments: Current patterns and emerging trends

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ABSTRACT

The public importance, wait-for-treatment ethos and clear geographic layout of Emergency Departments (EDs) has contributed to them being one of the most commonly modelled systems in healthcare Operational Research (OR). EDs are presently contending with higher than ever attendances, to which clinical research does not appear to have a comprehensive solution, whilst OR methodologies still need to command the trust of decision makers. With potentially greater acceptance of OR methodologies driven by heightened efforts to engage clinicians in evidence based approaches, we present a comprehensive review of the current literature. Whilst not the first in this area, our review is more broadly focused and thus able to serve both as a resource for modellers of methodology and study design, and as an introduction for decision makers. Our systematic literature search aimed to identify all English language papers from the year 2000 onward. We categorise papers using the defined dimensions of purpose, application area, method, scope and sponsor (originator).

Of 254 retrievals, we find that new publications are currently appearing at approximately 25 per year, up seven fold since 2000. We find positive trends in terms of recent publications (75% since 2008) as well as a trend towards achieving publication in journals, including healthcare related journals, which may assist in bringing simulation to a clinical audience and facilitating future engagement. The majority of projects appear to be of academic origin, based on Discrete Event Simulation, and focused on capacity, process and workforce issues at an operational level. However, the use of hybrid modelling may be associated with a more strategic outlook, as do projects originated at the request of healthcare organisations. We present a selection of case studies to illustrate both our classification and findings, and suggest directions for further research.

Contents

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1. Introduction

Hospital Emergency Departments (EDs) have been much studied in Operational Research (OR) although the extent of the existing literature remains uncertain. A number of reviews already exist, of which perhaps the broadest in scope have documented respectively 106 [1] and over 350 [2] publications. Several recent smaller reviews [3–5] highlight aspects of the system, particularly interventions around capacity issues and patient flows. These studies demonstrate that the history of ED modelling within OR stretches at least as far back as the 1980s, although the majority of papers are more recent. The essence of ED is an unscheduled, 'sit and wait' treatment system, albeit with differing levels of urgency ranging from immediate lifesaving intervention on the one hand, to the treatment of minor injuries on the other. Frequently, a substantial proportion of visits are made by patients who for specific reasons (for example, of convenience or community culture) prefer ED attendance to accessing primary care. Although the precise workings of the ED system may vary between different countries (for example in some countries, patients with minor to moderate trauma may be able to visit a specialist directly), the ED typically consists of a number of geographically distinct areas [6], each with its own queue distribution, namely the resuscitation ('resus') area, the 'majors' area dealing with more severe trauma alongside medical/surgical emergencies, and the 'minors' area catering for the least urgent conditions. There may also be a separate paediatrics area [7]. During quieter hours, all patients may be merged into a single area for convenience and to reduce staffing requirements. In this context, it is unsurprising, therefore, that queueing methodologies and Discrete Event Simulation (DES) are the most commonly employed modelling methods [4]. This, combined with the near universal geographical layout, has led to some interest in developing generic adaptable models of the ED, a concept that may help to save time and money in project work [8].

EDs in many countries, including in the UK (still commonly referred to as Accident and Emergency or 'A & E'), presently appear to be operating against a backdrop of previously unseen demand [9], leading to strains on available financial and staff resources [10] Until recently, EDs typically experienced a seasonal pattern in attendance. Attendances were higher in summer than in winter, however the lower winter attendance figures typically concealed a greater proportion of patients with more complex health needs who would regularly require acute admission [10]. This winter complexity pattern now appears to be becoming the norm, and is having a downward effect on performance metrics [10]. Thus, a common performance indicator for EDs is time, whether it be patient waiting time, treatment/consultation time, or overall time spent in EDs [11]. In the UK, this has been formalised, since 2005, into the 4-hour target, which mandates that 95% (formerly 98%) of patients must be seen, treated, and discharged from ED within this time [12]. Similar concepts have been developed elsewhere, borrowing from the 4-hour standard to a limited extent [13–15]. The impact of such targets are not completely understood. Supporters highlight evidence suggesting that delayed treatment is linked to increased patient mortality, whilst detractors note that the target appears to encourage gaming strategies with regard to selected patients (who may then cease to be of such interest once the target is missed) [6,16]. Questions as to what extent performance targets are useful is not the primary aim of this paper, although we will revisit this issue in the discussion section. Furthermore, it appears that supporting services such as primary care, social care and inpatient acute services are struggling to cope [10]. In recent years, research in the ED clinical sector [12] has sought to better understand the nature of so called ED 'crowding', to quantify it and to propose solutions.

Despite a low level of implementation [2], previous OR modelling of EDs has achieved a degree of recognition [17]. We therefore feel that, given the present struggles of EDs and recent emphasis on improving engagement with clinicians, the time is appropriate to thoroughly examine the current state of preparedness of healthcare OR with regards to working with EDs in future. Given not only the size, scale and importance of ED within the healthcare system, as well as the complexity and stochasticity of ED processes and related decision making, it is clear that decision support must follow a truly inter-disciplinary approach if implementation of the best possible solutions is to be achieved. Successful collaborations require understanding of the system from a variety of perspectives, the aim being to create sensible abstractions of a complex system that not only support policy making but also inspire confidence with staff and enable them to carry forward the interpersonal element of their role alongside any changes in working. Simulation approaches in OR have become tools of choice in this process.

Therefore, the aim of this review is to capture the existing literature on simulation studies in EDs as widely as possible. It is important to explicitly investigate the extent to which the existing body of literature addresses the actual problems in EDs and how well the studies support decision making. We also explore how this has been disseminated in relevant literature and examine its visibility, especially with regard to publications that are likely to be read by clinicians and managers. Whilst the focus of previous reviews appears to have been primarily on methods, patient flows and capacity, our overview is deliberately broader, in order to address this need. In addition to simulation methods, we also identify the following areas as being integral to why a study has been performed and how it relates to the present need:

- The overall purpose.
  What is the primary motivation for this work, i.e. is it enhancing OR methods and models or is it mainly service-driven?
- The application area(s).
  This dimension covers both the actual decision problem/setting and the relevant performance metrics.
- The study scope.
  Although the perceived majority of publications on ED tackles operational problems such as daily flow of patients, clearly ED operates within the broader context of both an acute hospital and alongside primary and social care systems in the community. Furthermore, EDs must not only respond to future demand but also recognise the changes in demand that are likely to occur as a result of pressures on this associated systems.
- The originator (sponsor).
  Papers with non-academic origin might potentially better serve the need for individually focused decision making in EDs.

The remainder of this article is organised as follows. After outlining the search strategy, we further enhance the rationale for the dimensions for our analysis (as listed above). We then present a quantitative analysis and highlight key findings from it, along with illustrative examples. Finally, we critically discuss how the existing literature can deal with existing problems in EDs and conclude our paper with an outlook to future research avenues.

2. Methods

2.1. Search strategy

2.1.1. Inclusion criteria

Studies eligible for inclusion were deemed to be any English language journal paper, conference proceeding or thesis published from the year 2000 to September 2016, that described a simulation model of/containing ED processes. We looked for any recognised simulation method such as DES, System Dynamics (SD), Agent based simulation (ABS), or Monte Carlo simulation/Markov Modelling. We felt that papers published pre-2000 were less likely to offer realistic insights into present ED operations, and that the most important papers published pre-2000 are well cited in previous reviews [1–4]. ED simulation modelling could be done in isolation or in the wider context of hospital patient flows or ambulance handover. We did not include papers that modelled, for example, Emergency Medical Services (EMS) or other healthcare processes entirely outside of ED, since they would be unlikely to give any insights into ED-specific operations. A recent EMS review has been published by Aboueljinane et al. [18]. Clinical training simulations were also excluded for this review.

Relevant studies as identified by citation searching were developed into a bibliographic database search (Appendix A). Publications that met the inclusion criteria were then identified by using combinations of search terms to create categories in Endnote. The definitive list was then created by hand searching of titles (Fig. 1). Reference lists of publications between 2013 and 2016 were checked for additional citations. We also provide an electronic database with all publications listed against the criteria of our analyses as an MS Excel file.

2.2. Dimensions

We felt that no paper could be described adequately purely in terms of a single focus such as modelling method or the core underlying planning task it was used to support. We therefore devised a structured five dimensional scheme to classify each paper. Classification of the papers was performed by the lead author. The first of five dimensions was the perceived overall **purpose** of the study. We recorded whether the paper had a strong research or method development purpose, or was directed primarily at quality improvement. Quality improvement implies that there must be areas of application in which the study aims to reveal potential improvements. Second, we considered the potential application areas of simulation studies in ED. Discussions between study authors identified the following categories of application.

- Managerial perspective
- Medical decision making.
- Patient behaviours
- Process and performance
- Resource and capacity
- Workforce planning

A study could be classified according to multiple categories (i.e. a single reviewed paper could appear in several categories). A managerial perspective is relevant because ED has an upward chain of accountability and operates under a model of financial remuneration per patient (the amount of which may be irrespective of clinical need). Under this heading we included financial aspects, cost-effectiveness, risk management and commissioning of new services. Currently a major issue in ED is the increasing case mix of patients with complex health needs. Although such patients are very likely to require admission, inpatient beds are not always available as required, whilst increasing length of stay in ED is associated with poorer health outcomes. In addition, the longer patients stay, the more likely it becomes that the financial remuneration will fail to cover the staffing cost and medications required. In a few cases, NHS trusts in the UK have responded to this need by commissioning their own social care teams to work in the community, thus facilitating earlier discharge of their medically fit inpatients and improving ED outflow [10].

Medical decision making is clearly central to the purpose of ED, and must operate efficiently in order to respond to target pressure. Under this heading we include any modelling of clinician interaction with patients, requesting of diagnostic tests (for example, blood, urine or radiographic), and decisions to admit or discharge a patient. On the one hand simulation modelling might investigate aspects of treatment pathway redesign, for example in situations where fresh clinical evidence or diagnostic test innovation can potentially facilitate improvement to current clinical protocols. On the other hand, factors such as the ratio of junior to senior staff may influence the efficiency of clinical decision making through, for example, the need for more junior staff to consult on complex management decisions.

Patient behaviours is aimed at simulation models that represent the effect of individual patient decisions. Although the most severely ill patients are unlikely to have much autonomy, there are clearly times of high demand when some patients who can may choose to leave without being seen (LWBS). Furthermore, patients under the influence of drugs and/or alcohol can exhibit challenging behaviour that can affect their treatment, for example injuries can be missed because the patient is less aware of pain and a full clinical survey is not performed.

Process and performance covers first the modelling of patient flows, for example, fast track options for selected patients when overall activity is high. Second, it examines ED processes such as the efficiency of clinical protocols. Third, we include any modelling around performance against targets, which, as previously stated, are often based around some measure of the time spent in the department. This is clearly very important in the current context, and has also been to some extent the focus of previous reviews.

Resource and capacity examines any model development and use around resources other than personnel, for example, bed capacity or other equipment. Usually, resource capacity and usage are important to capture in planning models, since this allows decision makers to assess the need, for example, for either changes in resource level (more or less) or alternative scheduling. This is clearly a complex area, since first, although many hospitals operate in modern buildings, some hospital buildings still exist which are decades old, and clearly were not designed with modern ED attendance levels in mind [10]. In extreme cases it has been reported that ED performance is constrained at times by lack of physical space [10]. Second, many hospitals are likely to have neither the available space nor resources to create extra facilities. In these cases, promoting more efficient use of available resources may be the only realistic option. Third, there will inevitably be times when resources are stretched by the needs of severely ill patients, and this may extend to diagnostics and laboratory services. Finally, in situations where the resource to expand facilities is available, simulation modelling can provide evidence as to whether this is the best course of action.

Workforce planning is focused on staff composition, numbers and deployment. In the current context where present resource

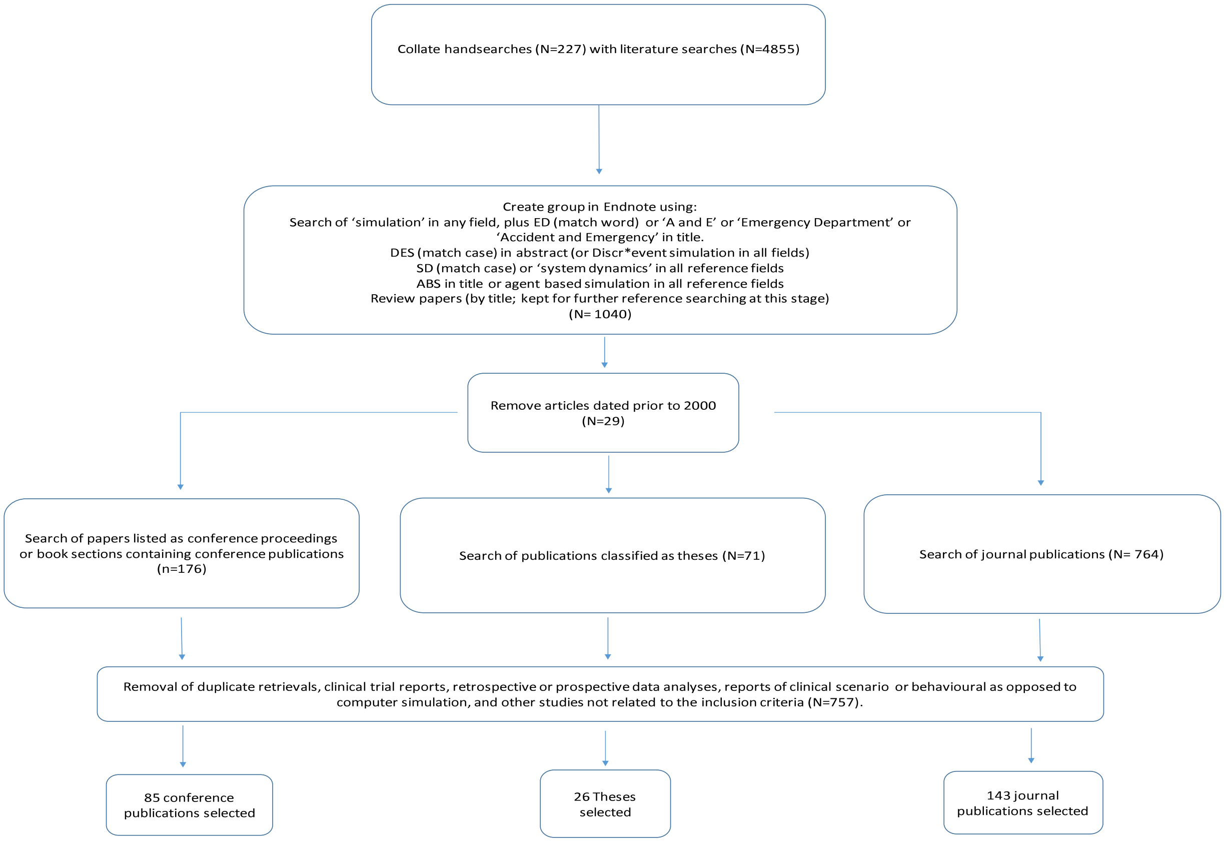

Fig. 1. Summary of literature search strategy.

may be insufficient, or recruitment and retention of permanent staff may be difficult then workforce utilisation, cohesion and morale are clearly important. Workforce utilisation might include aspects such as shift patterns or assignment of staff to tasks based on the experience necessary to complete them. A typical performance outcome might be patient wait time linked with staff type, number, experience level and cost. In contrast to many clinical systems, ED frequently faces the challenge that the sudden arrival of serious ill patients may require large numbers of staff to divert to that patient for a considerable length of time, which is likely to impact on performance elsewhere.

The third dimension is modelling methods. In addition to individual simulation paradigms, we explored the use of hybrid simulation methods (i.e. a combination of at least two distinct simulation paradigms), as well as adjunct mathematical or analytical approaches such as optimisation/heuristics, regression, or forecasting etc. We are also interested in the *explicit* use of qualitative methods (such as process mapping and other soft OR methods) alongside quantitative decision support.

The final two dimensions were called scope and sponsor. Scope captures the extent of the system modelled and whether the overall purpose of the study was perceived to be either on day-to-day operational level, or on a higher tactical or long term strategic level. It is clear from other evidence that ED is becoming increasingly dependent on the performance of adjoining systems (hospital acute care, primary care, social care) in order to be able to function efficiently. Hence we should be able to identify models that represent ED in that perspective. Sponsor identifies the originator of the research in terms of being either:

- Academic
- Health service
- Government
- Commercial sector

This scheme aims to comprehensively cover the range of activities commonly found in ED modelling studies. We believe this can prove useful both to modellers wishing to devise future studies as well as a means of analysing what research has been carried out and how it applies to the present problems of EDs.

2.3. Review procedure

Categories within each dimension were typically allocated by reading of the title, abstract, and keyword list (where available). In cases where the modelling method was not clear from this procedure, searching of the document (where available) using keywords "simulation", "software" or "discrete" was performed. Decisions about the originator of the research were made by scanning of introductions for any mentions of study origin, or by electronic search of the document using the terms "grant", "ackn(owledgement)", "confl(lict of interest)". In the case of an inconclusive search where the addresses of the authors were academic institutions, the work was deemed to be of academic origin. It was not felt sufficient to attribute any healthcare institutional involvement in designing a study simply on the basis of clinical authors in the publication list, since this collaboration might have only begun with the writing of the paper and as an aid to publication in a 'clinical' journal.

Assessing implementation and relevance

We hand screened retrievals that we considered to have an element of health service initiation in order to detect themes of current interest and for any account of clinical perceptions about the modelling work as well as any indications of policy changes.

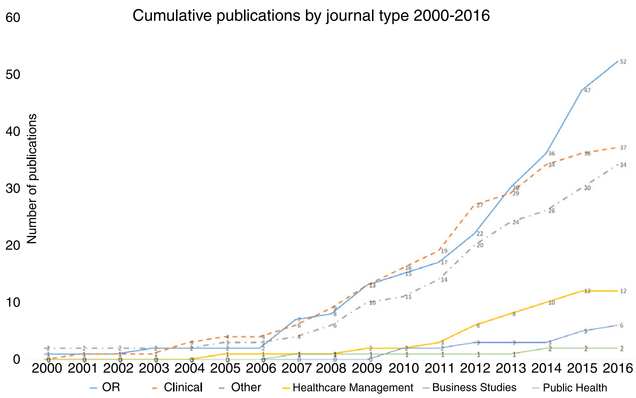

Fig. 2. Cumulative publications by journal type ($N = 143$ by end of study period).

Table 1
Characteristics of retrieved publications ($N = 254$).

DATE RANGE			NATIONAL ORIGIN	
Epoch	Total (%)	Mean per year	Country	Number (%)
2000–04	18(7.1)	3.6	USA	89(35.2)
2005–08	46(18.1)	11.5	UK	40(15.8)
2009–12	96(37.8)	24.0	Canada	20(7.9)
2013–16	94(37.0)	24.8	Spain	12(4.7)
			China	9(3.6)
			Israel	9(3.6)
PUBLICATION TYPE			France	7(2.8)
Type		Total (%)	Australia	5(2)
Journal publication		143(56.3)	Iran	5(2)
Conf. proceeding		85(33.5)	Ireland	4(1.6)
Thesis/Other		26(10.3)	Taiwan	4(1.6)
TOTAL		**254**	Other	49(19.4)

3. Results

3.1. Publication characteristics

We retrieved a total of **254** relevant publications dating from 2000 to September 2016, of which 56.3% were published in journals, 33.5% were conference publications and 10.3% were theses (Table 1). We divided the period of review into four intervals, of which the first (2000–4) spans five years and the last 3.75 years. The mean rate of publication per year over these time intervals has increased approximately seven fold over the entire period and by a factor of 2.1 since 2008. Overall almost three quarters of publications have appeared since 2008 (Table 1). In line with previously reported findings [1], there was a large spread of country of origin, although the majority of the publications were from the USA and UK (Table 1).

The number of journal publications increased overall, both in absolute numbers and proportion, from 7/18 (39%) in 2000–4, to 64/94 (69%) in 2013–16 (Fig. 2). The journal papers have been published in several domains, i.e. OR journals, clinical/medical journals, and healthcare management journals. Of the journal papers, 20.4% were published aiming at an OR audience (Fig. 2) and 14.5% at a clinical audience, with a further 4.7% aimed at healthcare management. The remaining publications appear in journals with a diverse array of subject areas such as business science, computer science and public health. Publication in OR audience journals appears to be increasing, along with those for business or computer science audiences. However overall publication in healthcare management journals is small, whilst the level of publication in clinically centred journals appears to be plateauing (Fig. 2).

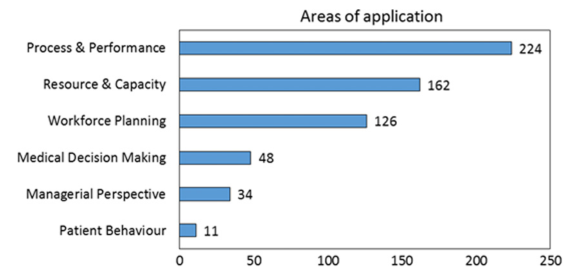

Fig. 3. Areas of application of retrieved studies.

3.2. Dimensional analysis

We present the aggregated results of our classification, along with a series of case studies. An individual classification on a per paper basis is provided in the supplementary Excel file.

3.2.1. Purpose and application area

We categorised 167 papers (65.7%) as being primarily concerned with quality improvement and 87 (34.3%) as having a substantial component of research orientation. This highlights that some of the papers did, in fact, use existing models to address a new problem. On the other hand, many of the papers have also developed new models in order to support a decision problem with a new and dedicated focus.

In terms of areas of application we found that 224 (88%) of studies were concerned with ED processes and performance whilst 162(64%) featured resource and capacity issues and 126(49%) examined some aspect of workforce planning (Fig. 3). Medical decision making, managerial aspects and individual patient behaviour were not commonly studied (Fig. 3). The concentration of results around the three largest categories, i.e. process and performance, resource and capacity and workforce planning, most likely reflects the flexibility with which simulation models can quickly investigate what-if scenarios concerned with either recruiting extra staff, adding more bed spaces or other analyses linked to patient flow. Clearly multiple examples could be illustrated for these categories. Abo Hamad and Arisha [19] used a 14 workstation DES model of a Dublin ED with the main hospital represented as a black box. This was linked to business methodologies (balanced scorecard) and integrated into a decision support system. The model was used to test the effect on the Irish 6 h performance target, of scenarios relating to capacity expansion, increased staff presence or unblocking the access block between ED and the hospital. In this context, the latter scenario was the only one significantly reducing average wait time in ED, in this case from over 9 h to 6 h. However this is a large category, and there are other examples of very different perspectives. Rashwan et al. [20] , for example, modelled the Irish health and social care system using an SD model that represented ED purely in terms of flows in and out of acute beds. Morgareidge et al. [21] used DES models of ED linked to space utilisation techniques to completely redesign a department. They also examined staff journey times between the ED and 12 hospital departments in order to determine the optimum location of a proposed new ED. In total we found four examples of capacity planning in the context of a new department.

In general, the low number of publications related to decision making, managerial perspective and patient behaviour (Fig. 3) suggests that there is potential to improve research in these areas especially considering the needs of complex patients. The difficulties of managing complex patients within the healthcare system are illustrated by Rashwan et al. [20] who further demonstrated that additional bed capacity is unlikely to produce more than

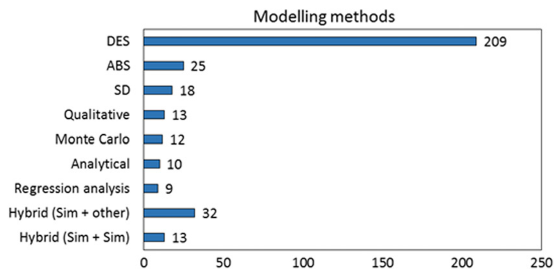

Fig. 4. Modelling methods identified.

short term relief to hospital bed occupancy. Rather, their results illustrated that the problem requires an integrated approach, based upon liaising with GPs (General Practitioners) to investigate other sources of care for potential admissions, as well as changes in the way long term care is managed. We identified very few other studies that explicitly addressed the needs of complex patients, however Vanderby et al. [22] built a whole hospital SD model which modelled flows between the ED and the major inpatient units. Their data analysis adjusted for patients deemed to be frail elderly, in terms of adjusted waits and process times. We also found very few papers that explicitly addressed financial aspects, in keeping with the findings of Gul et al. [1]. Morgareidge et al. [21] however underlined the fact that intuition about decision making, in this case relocating a department, can have important financial consequences, in this case an approximately $625,000 difference in 10 year operating cost. The financial impact of ambulance diversion on hospital revenues has also been examined (Pines et al. [23]). This issue is perhaps of more relevance in the US healthcare model than elsewhere owing to how that system is financed. Patient risk has been examined through the effect of triage systems, which are clearly fundamental to how long patients wait to be seen. However two patients with identical triage scores can have very different needs, and this was examined by Ashour et al. [24], showing that different algorithms can improve admission decision making. In terms of patient behaviour, it is perhaps unsurprising that this was most often examined using ABS models. Such methods are more recent, the earliest publication being 2008, and require a lot of process time. For example, Wang [25] described a model that appeared to represent mostly low acuity patients requiring simple treatments and minimal investigations. Interpersonal interactions were mostly initiated by staff, but simulated patients could decide to leave if their treatment progress was slow. Taboada et al. [26] were able to assign characteristics of staff experience and seniority to their modelled agents. This enabled them to assess, for example, the impact these might have on the efficiency of individual task completion. This, in turn, allowed them to investigate how the optimisation of departmental performance might be affected by potential variability amongst staff with regard to such characteristics. ABS is clearly able to support decision problems of this kind, however we did not identify any studies using ABS alone, that looked at ED in a broader context.

3.2.2. Simulation methods

In 209 papers, DES was the sole or main method of simulation (Fig. 4), and has also clearly featured in many of the case studies presented previously. ABS was found in 25 (9.9%) retrievals, SD in 18 (7.1%, Fig. 4) and hybrid models featuring either DES/SD or DES/ABS were the subject of 13 (5.1%) papers. We found that methods other than DES were often used to examine the influence of external factors upon ED waits. This has been illustrated already, for example by Abo Hamad and Arisha [13], and Rashwan et al. [20]. Ahmad et al. [27] add to the results of these studies using hybrid approaches, specifically, a parallel DES/SD approach. This study was in response to government targets imposed upon wait for treatment times in Malaysia. Some features of the system are different from those of European EDs, for example in that some ED staff also appear to have paramedic responsibilities in the surrounding community, and must therefore leave the department from time to time. The results however, confirm that ED length of stay may rise with higher hospital bed occupancy. In addition the study was able to examine relationships between ED waits and laboratory processes. As another example of relating bed occupancy to ED waits, Shi et al. [28] used a stochastic processing network to examine inpatient flows at hourly intervals. This illustrated that in their particular context, ED length of stay can be strongly influenced by discharge patterns and timing (for example, aiming to achieve substantial discharge proportions between 8 am–12 noon). Clearly such strategies are highly dependent on staff co-operation, and the study also examined the effect of staff shortages on discharge processes.

3.2.3. Scope and sponsor

There were 215 (85%) projects considered to be unit specific, and only 34 (13%) more generic. Many of the case studies so far would be considered to have high unit specificity, however examples such as Rashwan et al. [20] were also found, in which there were few if any locality specific features of the modelled system.

Study purpose

Overall, we found 67 (26%) projects that were considered to have an operational focus, compared with 79 (31%) a more tactical and 28 (11%) a strategic focus. A study could take in more than one of these perspectives. In our judgement, the distinction between these levels is found in terms of whether planned interventions are aimed more at smoothing day-to-day operations or at longer term objectives. Clearly there will be blurring of boundaries. In terms of examples, ED redesign (Morgareidge et al. [21]) or longer term changes in social care policy (Rashwan et al. [20]) could be considered strategic, and changes to hospital discharge policy (Shi et al. [28]) could be considered tactical or strategic.

In terms of sponsor (originator), 227 (89%) studies were judged to be chiefly or solely of academic origin. There were 18 studies with some evidence of government initiation/support after 2008 compared to 4 before. Ahmad et al. [27], for example, were supported by a national Ministry of Health grant. There were 12 publications with evidence of commercial sponsorship, including Morgareidge et al. [21], which also had an element of health service origin, itself a feature of 29 (11.4%) of publications. These latter publications were especially interesting to us for the potential insights they could give into the particular needs of the health service and whether or not greater engagement was more likely to lead to implementation. In this regard, we note that Morgareidge et al. [21] had a high engagement, and that changes were made to the design proposals based on the simulation model output. Vanderby et al. [22] which arose out of a situation where the model was commissioned to solve short term bed occupancy problems, also achieved a high level of engagement, and the attention of hospital directors.

As a final example of demonstrating engagement, Demir et al. [29] used forecasting and integrated decision support with user interfaces added to a DES model system to enable a UK hospital to make predictions related to future service need and increasing patient demand across three service areas, including ED. The addition of the user interface and the future proofing of the model system appear to have been influential factors in the clinician appreciation of the system's potential.

In addition, we examined the associations between modelling method and project scope. There is some evidence of a negative correlation between DES modelling and generic unit thinking, and

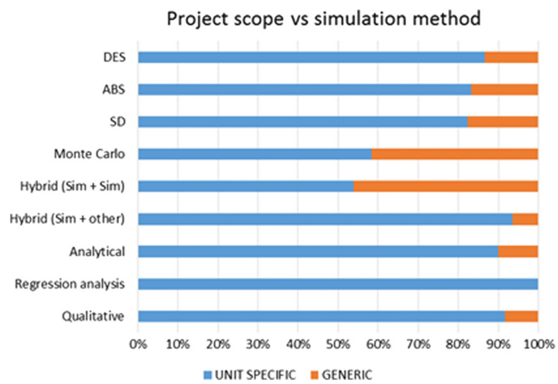

Fig. 5. Level of unit specificity vs modelling method.

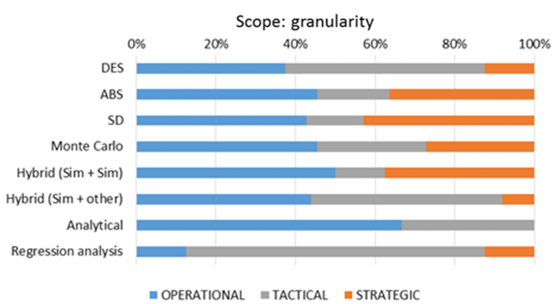

Fig. 6. Level of modelled change (operational, tactical, strategic) vs modelling method.

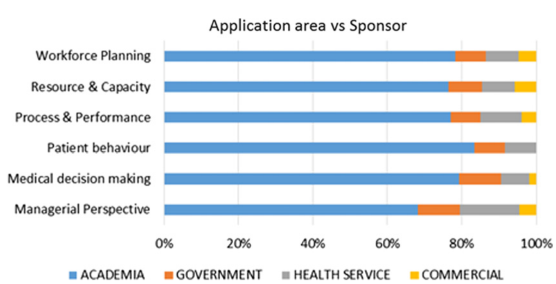

Fig. 7. Identified sponsors vs application area of study.

also that use of hybrid simulation is associated with more generic thinking (Fig. 5). Projects using SD, ABS or hybrid methods may have a more strategic focus than those employing purely DES +/- statistical methods (Fig. 6). The direction of these association is not clear, but taken together with the increasing needs of more complex patients in ED, it is likely that there will be found considerable potential for modelling projects that take a more strategic outlook along with increasing diversity of methods.

Finally we note that although managerial perspective accounted for only 34 (13%) papers, there is some evidence that a greater proportion of these studies were initiated in part by health services (Fig. 7). The direction of the association is again not clear but it may reflect the fact that, for example, financial concerns appear to be an everyday part of ED operations in the present climate, but have not been frequently addressed by simulation.

In order to provide a degree of context for our findings, we compare these with a selection of other recent reviews (Table 2). We search a shorter timeline, however due to our general theme, we retrieve substantially more publications typically than recent works. We present the only fully systematic and specified literature search for a work of this size and scope. Our taxonomy covers a greater dimensional scope, and we summarise our findings for easier reference.

4. Discussion

We retrieved 254 publications over the 17 years of the search, spanning 38 different countries. Clearly this indicates that ED is considered an important clinical area, and that OR simulation methods are considered broadly applicable to ED worldwide, in line with the findings of Gul et al. [1]. Furthermore, the literature has clearly grown considerably in recent years and continues to grow. Hence we find that 75% of these papers have appeared since 2008 and the rate of publication currently stands at approximately 25 papers per year, compared to approximately 3 per year at the beginning of the study period, which, taken together with the modest trend in government sponsored projects, may reflect a genuine increase in interest in the applications of OR to healthcare. We note that data gathering methods in some countries (for example, Malaysia) [27] reportedly make it more difficult to access sufficient data to build models. In terms of dissemination, we observed an increasing tendency to publish work in journals (68% of all publications since 2012 compared to, for example, 40% in the years 2000–8), with 14.5% of papers were published in clinical medical journals. We recognise that to some extent our results reflect a number of instances of dual publication of closely related subject matter, in both journals and conference proceedings, that they also depend on the extent of conference database and 'grey literature' searching, and that a review based around English language articles may be prone to positive bias in terms of papers originating from English speaking countries. We are however confident that our search of important conference databases was thorough, and that any potential language bias does not seriously hamper any conclusions of our work in the context of a system which is broadly recognisable in its core elements irrespective of the country of origin [7,27,30].

The large number of studies that we retrieved appears to be divided approximately 2:1 in terms of whether the focus was primarily addressing issues of quality improvement in a (usually) specified ED system, or developing more sophisticated methodologies to analyse such systems. It is hard to judge whether this division is appropriate, since clearly enhanced methodology is likely to be of benefit, with one important caveat that we will address further. On the other hand, it is intuitively obvious that the greater degree of research effort should be directed towards applying existing methodology to solve present problems. A further consideration is the targeting of clinical readership as a way of increasing confidence in simulation. In this context, we find that 14.5% of our retrievals, amounting to 37 of our 254 publications, are targeted at this readership. It is likely that this is the only window for simulation to be viewed by clinicians, since they reportedly spend little time on related reading, tend to read abstracts only, and may rely on commercial non-peer reviewed literature [31,32]. Thus this engagement opportunity is potentially small, and we feel very effort should be made to maximise it by targeting publication far more in this direction as well as to traditional OR journals.

We further found that in terms of application, the emphasis has been largely on processes, resources and capacity and workforce planning. Aspects such as patient behaviour, were largely associated, as expected, with ABS methods, although other methods are possible [33,34]. However, Discrete Event Simulations made up the majority of simulations, projects appeared to be largely initiated by academic departments, and most presented themselves as being concerned with processes at a day to day operational level. We did find however, several simulations that considered ED as part of a larger system, whether a whole hospital or a complete acute health and social care system. A greater variety of modelling approaches were found within these examples, including hybrid simulation approaches and greater use of SD. Furthermore, our findings indicate that strategic and managerial aspects were considered important by health service personnel, since they featured

Table 2
Comparison of this review with recent published reviews.

	Saghafian et al. [2]	Gul et al. [1]	Paul et al. [4]	Mohiuddin et al. [5]	Present review
Number of papers included	350	106	43	21	254
Temporal scope	Not specified, but citations go back to 1980s.	1968–2013	1970–2006	1946 2016	2000–16
Theme of review	Patient flow studies	ED performance in usual and disaster scenarios	Crowding	Patient flow studies with UK NHS	Simulation applied to ED in any context
Inclusion criteria reported?	No	Yes	Yes	Yes	Yes
Search specified and reproducible	No details given of search strategy	Limited details given, not completely reproducible	Yes	Yes	Yes
Methodology (OR)	Multiple including simulation, queue, theory, mathematical, game theory.	Simulation	Simulation	Simulation	Simulation + hybrid approaches
Studies analysed by dimension (which)	Narrative description only	Yes (aim, KPIs, data gathering method, software). No summary	Yes (motivation, data collection, scenarios tested). No summary	Yes (Purpose, software used, inputs and outputs, validation, stakeholder involvement).	Yes(Purpose, application, method, scope, sponsor)
Commissioners of study.	No	No	No	Stakeholder involvement in proposing study question and model specification reported. Stakeholder assumed to be UK NHS institution in all cases.	Yes
Data sources/ collection methods	Yes	Yes	Yes	Yes	No
Individual study results	Some studies, generally descriptive	Yes	Yes	Yes	Selected studies, descriptive
KPIs reported	Narrative review of scenario testing	Yes	Summary of scenario testing		Summary of scenario testing
Software used	Yes	Yes	Yes	Yes	No
Publication channel (i.e. type of journal)	By citation only	Yes	Yes	Yes	Yes

more prominently in the 11% of studies in which we discerned some degree of health service initiation.

We feel that our work significantly extends what has been achieved in previous reviews of OR applied to ED. A summary of some recent studies (Table 2) shows, for example that although we do not report on studies published prior to the year 2000, we present the most comprehensive list of simulation projects relating to ED, based on a reproducible systematic literature search. By contrast, the search strategy of Saghafian et al. is not reported, and the selection of exemplar studies for each aspect of the flow pathway is not explained. The search strategy of Gul et al. contains too few details to be fully reproducible, whilst the reviews of both Paul et al. and Mohiuddin et al. are based on a more limited focus. In keeping with the theme of our work as a broad overview, we preferred the presentation of application areas to that of KPIs, as we felt that readers may initially be more interested in an area of system application rather than what precisely was measured. Also, many studies have multiple outcome measures and test several 'what if' scenarios, so the resulting summaries are difficult to assimilate into any coherent understanding if presented in a largely narrative style. Similarly, we felt it unnecessary to report the software packages used for the same reason, concentrating rather on the simulation methods.

A similar multi-dimensional approach to ours has been used previously to examine OR in healthcare generally. This study was based on heuristic sampling of an enormous number of papers [35]. Our task was to review the ED simulation literature at unit level, which we felt was achievable. As such, we recognise some dimensions in Brailsford's taxonomy that resonate with our own (methods, initiators, functional area as opposed to application area) and others that are perhaps at a higher level of observation (layer in the industry). We also report on country, databases and year of publication. Our assessment of what constitutes an aspect of functional area/application area arguably differs from theirs primarily due to the fact that ED is a much more concrete entity, even in functional as opposed to purely geographical terms, than the myriad healthcare applications of OR sampled by Brailsford et al. We find some evidence of a similar dimensionality appears in reviews of ED modelling, but arguably to a less complete extent. As argued in Brailsford et al., the value of providing a taxonomy for OR studies, compared to a narrative review, is the sense of structure and coherence that it brings. In the present review, we also provide summary evidence relating to each study, and in doing so, also provide a resource both for the modeller, and the seeker of simulation based evidence. As such, our approach therefore brings a greater coherence to this area of OR, and extends the presentations or recent authors (Table 2). In terms of more direct comparison, Paul [4] refers to motivations, which are subdivided into costs and competition, efficiency, re-engineering, and quality of service. This would be analogous to our application areas, which we feel are somewhat more extensive in that not only do they take account of financial, resource and workforce issues (∼efficiency), but also consider the modelling of clinical decision making and patient behaviour. Gul et al. [1] provide a descriptive account of each study's aims, without an attempt to categorise, and therefore a straightforward comparison is not possible. Mohiuddin et al. [5], in addition to purpose, methods and software, also examine stakeholder involvement, where this can be deduced. However, we also take into account both the level of strategic planning that the study is capable of addressing, and also attempt to pinpoint the precise owner of the work, which we fell goes a degree beyond involvement. This latter characteristic is potentially very useful since knowing, in effect, who prompted the work to be done show both a degree of engagement and also insight into the main perceived problems with the system. Unfortunately we found that this precise information was unavailable in most of the reports.

We acknowledge that our classification process cannot claim full methodological rigour owing to the fact that the work was carried out by a single author (AS). That said, we would expect a very high level of agreement on simulation method, as this is usually stated in the title or abstract or keywords, and if not found here, can be deduced from the model diagram or software used. In terms of the other dimensions, we used an informal judgement process which was discussed amongst the study authors. Typically, in terms of scope, a project write-up had to be clear that there was a broader objective to the modelling to classify a project as 'tactical' or 'strategic' in outlook, and since most projects were very ED centric, and also probably unsolicited, it is likely that our estimations of these as purely 'operational' in outlook are accurate. Our classifications of sponsor required an explicit statement that someone other than an academic author had initiated the project. It was not enough simply to find a clinical author attached to the publication or a general acknowledgement of assistance. Very often, little explicit information was provided, for which we feel the most likely explanation is that most projects we reviewed did not have a high level of clinical engagement.

One the one hand, having a large number of studies concentrated around a few areas of application makes for a large potential resource. Also, there could be little doubt that system performance as measured by patient flow and targets, workforce, and other resource issues are important areas of application. Given the ongoing appearance of studies however, our main hope for the future is that these increasingly shift focus to examine influences outside of ED, since there is evidence from expanded system models that these are likely to be important. We note this is a view shared by other recent reviewers in this area. Paul [4], Gul [1], Saghafian [2] and Mohiuddin [5], for example, also variously suggest an increase in the use of multi method modelling, explicit justification of the modelling method, or methods designed to further explore the effect of patient behaviour, as well as better data collection and use. Although they do not quite say so, Gul et al. [1] may also be referring to the need to consider the relative costs of 'what if' scenarios, and that in a resource limited world, the 'no brainer' scenario may simply not be possible. Hence future simulations and 'what if' scenarios must include an informed cost analysis. We would certainly agree that all of these recommendations have merit. We feel, however that there is a more fundamental issue.

In our introduction we raised two questions that appear to be closely related, namely, to what extent does present research speak to current issues in EDs and to what extent do the studies support decision making? However, despite the fact that over 250 publications relating to ED simulation exist, and a further number based on queuing models, these questions turn out to be challenging. Paul et al. [4] report that as early as 2001, the US National Academy of Engineering, and Institute of Medicine jointly spoke of the 'knowledge/awareness divide' that was (and in our opinion still is) 'separating healthcare professionals from their potential partners.' The utility of simulation was especially stressed. On the one hand, there now exists a much larger volume of work, many of which examine plausible scenarios and promise substantial benefits. We highlight a number of studies, with a variety of methods and system perspectives (e.g. Rashwan et al. [20], Vanderby et al. [22], Ahmad et al. [27], Shi et al. [28], and Wong et al. [36]), that generate important insights over a diverse range of applications from patient triage to elderly patient discharge, and even very fundamental pre-operational issues such as department location and geography (Morgareidge et al. [21]). Unfortunately, the follow through from experimentation to implementation to assessment of actual benefit has generally not been accomplished. We agree with Saghafian et al. [2] that this is not just down to awareness issues. Further, we strongly suspect that the 'accelerated publication' argument [5,37] is mostly a veneer for: not just lack of knowledge but also lack of belief in the findings of largely unsolicited research, lack of engagement, and, although the 'not done (invented) here' syndrome may also be operating, there is likely to be a genuine difficulty in the present resource climate, in taking a risk on change that is costly. It may be helpful, therefore, for simulation builders to consider including an implementation plan, even when the purpose of the publication is method development orientated. If this results in fewer unsolicited research projects, then probably so much the better. We would further support Gul et al. [1] in their contention that meaningful results can only be achieved with a comprehensive cost analysis, and we would add that societal pressures may also be important, for example, potential staff may not wish to relocate to areas where, for example, the school provision is perceived to be poor, therefore rota gaps have to be filled by expensive agency staff etc. In short, what we have at present is a huge selection of varied but largely untested proposals, many intuitively sensible, but unless transferred faithfully and confidently to the actual system, cannot be rigorously evaluated. Debates around the best choice of method might also need to be placed in this context.

In terms of the present need, Paul et al. [4] further note that problems of overcrowding in EDs had, in their opinion, reached critical levels in the USA by 2010. Wiler et al. [3] cite the findings of the 2009 US Government Accountability Office report, whilst, in a wide ranging introduction to their review, Saghafian et al. [2] cite a variety of statistics, mostly between c. 1990–2005, that all support this appraisal. They also correctly note that this system acts as a first point of healthcare for many people. It is also likely that, especially in countries where healthcare is otherwise largely self-funded, that in many cases it is the only one. Gul et al. [1] further remind us that ED is also the first point of access in disaster situations. More recently in the UK, it has been reported that the number of patients spending more than 4 h in EDs here has increased from 700,000 (5% of all patients) in 2011–12, to 1.8 million (12% of all) in 2015–16 [10]. Consequently, although the issue of (over)crowding has only more recently begun to be better defined and researched in the UK, this is now a growing area of exploration amongst ED clinicians. For example, Boyle et al. [38] describe recently developed tools to measure crowding in ED, and assess staff perceptions of patient safety. Mason et al. [39] review the evidence around so-called access block, and discuss various approaches, such as capacity and staff increases, better coordination with mental health services, and a selection of service redesign initiatives. Interestingly, the only referenced study aimed at improving inpatient discharge performance [36], was a simulation model.

It is in this context therefore, that recommendations regarding the future orientation of ED simulation must be placed. A greater degree of effort in examining external influences appears to be almost essential. These might include for example, hospital inpatient factors, or General Practice (GP), or community social work factors. We also understand the desire for more features of the real system to be somehow taken account of in creating models. ED is undoubtedly complex. However, we urge caution on two fronts. First, that the situation does not arise whereby there is simply an accumulation of yet more studies, with further suggested untested interventions. However complex, a model will never be completely authentic, a fact quickly apparent to any disengaged critic. A change in modelling focus, therefore, must take place in a context of managed engagement. Also, as the proposed solutions move further from the operational heart of ED, they are more likely to conflict with other priorities, and require the engagement of a wider group of people whose time demands are thinly spread, e.g. GP, social work, EMS, ITU clinicians etc. Furthermore, unless the parties are clear that they are in the room specifically because their sector of the service potentially wields the greatest influence over whether or not the ED can fulfil its basic obligations to the community, then little will be achieved. In a resource limited environment therefore, we need to know where to spend the money. This is a present urgent need, given that those currently working in EDs repeatedly stress how the system is continually having to operate at highly undesirable levels of demand [10]. We feel that what this requires is actually some, potentially quite simple, modelling around the following questions: What measures are available of whether the system is even able to cope? Given that from time to time, performance will fall behind target, how much time does the system typically spend in this state, what measures are required to help it to recover, and to what stresses is it most susceptible? This could be crisis scenario, a general increase in demand, or the inability of the hospital to find adequate social care for medically fit patients. For example, the impact of several multiply injured patients arriving, may be quite different to a mere increase in demand across patients in lower priority triage categories, since, for example, staff committed to the care of the highest priority triage patients cannot realistically be expected to be available for other patients' needs in the meantime. Thus, the emergency requires resources that may be measured in whole doctor or nurse hours to handle, even if not all that time is actively expended. This situation is further complicated by the imposition of targets. If a target is in place, then at any given time, a minimum number of such 'resource hours' must generally be available, or the system will repeatedly fail. The answers to these questions will then guide the development of realistic solutions.

5. Conclusion

Since 2000 there have been over 250 publications on the subject of ED modelling which we find to divide broadly 2:1 in terms of being purely service directed compared to having some degree of research component. The rate of publication appears to be increasing and currently stands at around 25 papers per year. The present situation is a mixed picture. On the one hand we found important examples of well engaged work. However, these were few, and we also find an under emphasis on strategic thinking, financial issues, individual patient issues of behaviour, clinical problem complexity and non-medical need. If as seems likely, simulation must broaden its focus to also examine system influences outside of ED itself, it is essential first, that this takes place in well engaged context, and also, in the present climate, that there is a clear idea of which particular system influences will most benefit from the limited extra resources that are likely to be available.

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Table A.1
Web of Science search strategy.

1. TS = (emergency near/5 (department* OR room* OR unit* OR ward* OR care))
2. TS = ("accident* and emergenc*")
3. #2 OR #1
4. TS = (simulation* OR simulate* OR simulating)
5. TS = (model* OR "system dynamic*" OR "decision support system*" OR "patient flow" OR "agent-based" OR "capacity plan*")
6. #5 OR #4
7. #6 AND #3
8. TOPIC: (queue* OR queuing OR overcrowding OR crowding OR disaster* OR "patient experience" OR bottleneck* OR workflow OR "patient flow" OR "length of stay" OR "bed configuration*")
9. TOPIC: (schedul* OR reschedul* OR restructur* OR reorgani* OR redesign* OR decision support OR resource allocation)
10. TOPIC: (optimi?ation OR performance OR efficiency OR capacity OR time* OR cost* OR process*)
11. #10 OR #9 OR #8
12. #11 AND #7

Appendix A. Literature search strategy

Initial background searches to identify relevant studies involved checking the reference lists of authors known to have published research on ED modelling. This was extended to citations of studies thus retrieved using Google Scholar. These searches identified circa 221 papers including a recent systematic review of A&E simulation studies which included 106 potentially relevant studies (Gul 2015) [1]. Web of Science indexed the majority of relevant studies identified by the background searches and was thus used to develop the bibliographic database search strategy.

The first draft search strategy combined search terms for A & E with search terms for modelling using the AND Boolean operator. This search retrieved circa 10,000 hits in Web of Science, including many studies which did not meet the inclusion criteria. A more focused search was developed by adding a third set of search terms which were derived from the titles and abstracts of relevant studies identified in the background searches and supplemented with relevant synonyms. These terms described either (a) the main problems addressed by A & E simulation (for example, overcrowding, queueing, patient flow) or (b) outcomes (for example, improved resource allocation, performance, and reorganisation). A sample set of 100 studies was screened to eliminate inefficient search terms from this third set of terms. For example, the search terms "time" and "cost" were identified as not useful, since these did not uniquely identify any relevant papers in the sample set. This further helped to eliminate irrelevant studies from the final set of results.

The final search was translated for use in an appropriate selection of databases and run on 17th September 2016. The following databases were searched: Web of Science (Thomson Reuters) including the Science Citation Index, Social Science Citation Index, Science Conference Proceedings Citation Index and Social Science Conference Proceeding Citation Index; MEDLINE (Ovid), the Cochrane Database of Systematic Reviews, CENTRAL, the HTA database and NHS EED (all via the Cochrane Library); ProQuest Dissertations and Theses (ProQuest); and EconLit (EBSCO). These databases provide coverage of the studies identified in the background searches, including grey literature such as conference abstracts via the Web of Science conference proceeding citation indexes and dissertations via the ProQuest Dissertation and Theses database.

The results of the bibliographic database searches were exported to Endnote X7 and de-duplicated using automatic de-duplication and manual checking. In addition, the full set of references from Gul 2015 [1] ($n = 125$) were exported to Endnote and de-duplicated against the bibliographic database search results. A total of 4856 unique references were identified. The final database contained 5083 entries (see Table A.1).

Appendix B. Dimensions of the classification with unit results for each dimension

Dimension and categories	References
PURPOSE	
Method-driven	2, 4, 6, 8, 9, 12, 17, 18, 20, 22, 24, 25, 27, 29, 30, 33, 36, 37, 40, 41, 44, 52, 55, 58, 60, 61, 62, 63, 64, 65, 67, 68, 69, 71, 72, 73, 74, 76, 81, 88, 90, 91, 92, 94, 96, 98, 106, 107, 108, 110, 112, 116, 120, 122, 128, 134, 148, 151, 152, 158, 159, 160, 162, 164, 166, 169, 170, 171, 174, 183, 186, 189, 190, 200, 201, 203, 205, 211, 213, 214, 218, 220, 221, 222, 228, 238, 246
Quality Improvement	1, 3, 5, 7, 10, 11, 13, 14, 15, 16, 19, 21, 23, 26, 28, 31, 32, 34, 35, 38, 39, 42, 43, 45, 46, 47, 48, 49, 50, 51, 53, 54, 56, 57, 59, 66, 70, 75, 77, 78, 79, 80, 82, 83, 84, 85, 86, 87, 89, 93, 95, 97, 99, 100, 101, 102, 103, 104, 105, 109, 111, 113, 114, 115, 117, 118, 119, 121, 123, 124, 125, 126, 127, 129, 130, 131, 132, 133, 135, 136, 137, 138, 139, 140, 141, 142, 143, 144, 145, 146, 147, 149, 150, 153, 154, 155, 156, 157, 161, 163, 165, 167, 168, 172, 173, 175, 176, 177, 178, 179, 180, 181, 182, 184, 185, 187, 188, 191, 192, 193, 194, 195, 196, 197, 198, 199, 202, 204, 206, 207, 208, 209, 210, 212, 215, 216, 217, 219, 223, 224, 225, 226, 227, 229, 230, 231, 232, 233, 234, 235, 236, 237, 239, 240, 241, 242, 243, 244, 245, 247, 248, 249, 250, 251, 252, 253, 254
APPLICATION AREA	
Managerial perspective	7, 13, 21, 29, 30, 32, 35, 43, 45, 50, 66, 76, 78, 79, 81, 99, 100, 101, 108, 110, 113, 141, 145, 149, 177, 178, 193, 201, 204, 207, 231, 242, 251, 252
Medical decision making	2, 7, 22, 29, 30, 32, 44, 45, 54, 59, 60, 62, 70, 75, 77, 86, 89, 93, 95, 118, 120, 121, 125, 133, 139, 140, 144, 146, 153, 156, 162, 163, 165, 174, 179, 180, 191, 206, 216, 218, 221, 222, 232, 235, 240, 241, 242, 252
Patient behaviour	31, 56, 88, 93, 98, 153, 162, 218, 220, 221, 222
Process & Performance	2,3, 5, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 22, 23, 25, 26, 27, 28, 29, 30, 31, 32, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111, 112, 113, 114, 115, 116, 117, 118, 119, 120, 121, 122, 123, 124, 125, 126, 127, 128, 130, 131, 132, 133, 134, 136, 137, 138, 139, 140, 141, 142, 143, 144, 145, 146, 147, 149, 150, 151, 152, 154, 155, 156, 157, 158, 159, 160, 161, 162, 163, 165, 167, 168, 169, 170, 171, 172, 173, 174, 175, 177, 179, 180, 181, 182, 183, 184, 185, 186, 187, 188, 189, 190, 191, 192, 196, 197, 198, 200, 201, 202, 204, 205, 206, 207, 208, 210, 211, 212, 213, 214, 215, 216, 217, 218, 219, 222, 223, 224, 225, 226, 227, 228, 229, 231, 232, 233, 234, 235, 236, 237, 239, 240, 241, 242, 243, 244, 246, 247, 248, 249, 250, 251, 253, 254
Resource & Capacity	1, 2, 3, 6, 7, 9, 10, 11, 13, 14, 16, 18, 20, 21, 24, 29, 30, 31, 32, 33, 34, 36, 38, 39, 42, 43, 44, 45, 46, 47, 49, 50, 59, 63, 66, 68, 69, 70, 71, 73, 75, 76, 77, 78, 79, 80, 81, 83, 84, 85, 87, 89, 92, 93, 94, 97, 99, 100, 101, 103, 104, 105, 107, 109, 110, 111, 115, 116, 118, 119, 120, 121, 122, 123, 124, 125, 128, 129, 130, 131, 133, 134, 135, 137, 139, 140, 142, 143, 144, 145, 146, 147, 149, 152, 154, 155, 156, 157, 158, 159, 160, 161, 163, 165, 166, 167, 173, 174, 176, 177, 178, 179, 181, 182, 183, 184, 186, 187, 188, 189, 190, 191, 193, 196, 197, 198, 199, 201, 202, 203, 204, 206, 207, 208, 214, 215, 216, 218, 221, 222, 223, 224, 225, 227, 229, 231, 234, 238, 239, 240, 241, 242, 243, 244, 245, 246, 247, 248, 249, 251, 252, 253, 254
Workforce planning	1, 3, 6, 7, 9, 10, 11, 12, 13, 14, 16, 19, 21, 25, 28, 29, 30, 32, 34, 35, 38, 43, 44, 46, 48, 49, 50, 53, 54, 56, 57, 59, 63, 66, 68, 70, 71, 72, 77, 78, 79, 80, 81, 82, 84, 86, 87, 94, 96, 97, 100, 101, 103, 104, 105, 106, 107, 109, 110, 111, 113, 114, 117, 119, 121, 122, 123, 124, 127, 128, 131, 132, 133, 134, 135, 139, 141, 145, 146, 149, 152, 154, 158, 160, 161, 169, 170, 174, 179, 180, 184, 185, 187, 189, 190, 191, 195, 198, 199, 202, 206, 209, 210, 217, 218, 223, 224, 225, 226, 227, 229, 230, 231, 232, 233, 234, 235, 236, 237, 238, 239, 247, 249, 250, 251, 252, 253
MODELLING METHODS	
DES	1, 2, 4, 5, 6, 7, 8, 9, 10, 11, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 34, 35, 36, 37, 38, 39, 40, 41, 43, 44, 46, 47, 48, 49, 50, 51, 52, 53, 54, 58, 59, 60, 61, 63, 64, 65, 66, 67, 68, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111, 112, 113, 114, 115, 116, 118, 119, 120, 121, 122, 123, 124, 125, 128, 129, 130, 131, 132, 133, 134, 135, 137, 138, 139, 140, 141, 142, 143, 144, 145, 146, 147, 148, 149, 150, 155, 156, 157, 158, 159, 160, 161, 163, 167, 168, 169, 170, 171, 172, 173, 174, 175, 177, 178, 179, 180, 181, 182, 183, 184, 185, 186, 188, 189, 190, 191, 192, 193, 195, 196, 198, 199, 202, 203, 204, 205, 207, 208, 209, 211, 212, 213, 214, 215, 223, 224, 225, 226, 227, 228, 230, 231, 232, 233, 234, 236, 237, 239, 240, 243, 244, 246, 247, 248, 249, 250, 251, 252, 253, 254
ABS	4, 12, 40, 41, 55, 56, 57, 62, 88, 127, 135, 136, 153, 154, 162, 174, 200, 217, 218, 219, 220, 221, 222, 235, 238
SD	2, 33, 34, 42, 64, 65, 69, 126, 151, 152, 155, 165, 187, 197, 216, 229, 241, 242
Monte Carlo	3, 117, 122, 164, 166, 176, 177, 178, 201, 206, 210, 245
Hybrid (Sim + Sim)	2, 4, 34, 40, 41, 64, 65, 122, 135, 155, 174, 177, 178
Hybrid (Sim + other)	3, 23, 28, 29, 30, 79, 114, 115, 117, 121, 126, 130, 131, 141, 154, 156, 160, 166, 175, 179, 185, 186, 189, 191, 193, 206, 210, 211, 214, 216, 238, 245
Analytical	3, 23, 117, 121, 154, 160, 166, 206, 210, 211
Regression analysis	79, 115, 131, 156, 175, 189, 191, 193, 245
Qualitative	28, 29, 30, 114, 126, 130, 141, 179, 185, 186, 214, 216, 238
SCOPE	
Unit specific	1, 2, 3, 5, 6, 7, 9, 10, 11, 12, 13, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 42, 43, 44, 45, 46, 47, 48, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 69, 70, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 93, 97, 98, 99, 100, 101, 102, 103, 105, 106, 107, 108, 109, 110, 111, 112, 113, 114, 115, 116, 117, 118, 119, 120, 121, 122, 123, 124, 125, 127, 128, 129, 130, 131, 133, 134, 135, 136, 137, 138, 139, 140, 141, 142, 143, 144, 145, 147, 148, 149, 150, 151, 152, 153, 154, 156, 157, 158, 159, 160, 161, 162, 163, 165, 166, 167, 168, 169, 171, 172, 173, 175, 179, 181, 182, 184, 185, 186, 187, 188, 189, 190, 191, 192, 193, 195, 196, 198, 199, 201, 202, 203, 204, 206, 207, 208, 211, 216, 217, 219, 220, 221, 222, 223, 224, 225, 226, 227, 228, 230, 231, 232, 234, 235, 236, 237, 238, 239, 240, 241, 242, 243, 244, 245, 246, 247, 248, 249, 250, 251, 252, 253, 254
Generic	4, 14, 41, 49, 53, 67, 68, 71, 91, 94, 95, 96, 104, 126, 132, 146, 155, 164, 170, 174, 176, 177, 178, 180, 183, 197, 200, 205, 209, 210, 212, 213, 215, 233

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Strategic	10, 12, 13, 42, 71, 79, 94, 104, 105, 107, 118, 126, 134, 138, 147, 153, 155, 165, 167, 176, 177, 178, 181, 182, 197, 200, 219, 229
Tactical	3, 7, 11, 16, 19, 29, 30, 31, 32, 36, 43, 44, 45, 47, 50, 60, 66, 69, 73, 75, 76, 79, 81, 84, 85, 87, 97, 100, 101, 103, 106, 109, 115, 119, 123, 124, 125, 133, 135, 139, 141, 143, 144, 149, 152, 159, 161, 163, 172, 173, 175, 189, 190, 191, 192, 196, 199, 202, 206, 214, 223, 225, 226, 227, 228, 230, 231, 234, 235, 237, 239, 244, 245, 246, 247, 248, 249, 250, 251
SPONSOR	
Academia	1, 2, 3, 4, 7, 9, 10, 11, 12, 14, 15, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111, 112, 113, 114, 115, 116, 118, 119, 120, 121, 122, 123, 124, 125, 127, 128, 129, 131, 132, 133, 135, 136, 137, 138, 139, 140, 141, 142, 143, 144, 145, 146, 147, 148, 149, 150, 151, 152, 153, 154, 155, 156, 157, 158, 159, 160, 161, 162, 163, 164, 165, 166, 167, 168, 169, 170, 171, 172, 173, 174, 175, 177, 178, 180, 183, 184, 185, 186, 187, 188, 189, 190, 191, 192, 195, 196, 198, 199, 200, 201, 202, 203, 204, 206, 207, 208, 209, 210, 211, 212, 213, 214, 215, 216, 217, 220, 221, 222, 223, 224, 225, 226, 227, 228, 230, 231, 232, 233, 234, 235, 237, 238, 239, 240, 241, 242, 244, 245, 246, 247, 248, 249, 250, 251, 252, 253, 254
Government	31, 32, 42, 50, 66, 70, 87, 89, 95, 96, 115, 131, 149, 157, 163, 205, 206, 213, 236, 238, 248, 251
Heath service	13, 29, 30, 51, 52, 53, 60, 79, 93, 99, 111, 112, 113, 114, 117, 126, 136, 143, 145, 155, 157, 160, 167, 172, 182, 197, 202, 219, 229
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Appendix C. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.orhc.2018.01.001.

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