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Emergency department resource optimisation for improved performance: a review

Kazi Badrul Ahsan¹ · M. R. Alam¹ · Doug Gordon Morel¹ · M. A. Karim¹ 

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Abstract

Emergency departments (EDs) have been becoming increasingly congested due to the combined impacts of growing demand, access block and increased clinical capability of the EDs. This congestion has known to have adverse impacts on the performance of the healthcare services. Attempts to overcome with this challenge have focussed largely on the demand management and the application of system wide process targets such as the “four-hour rule” intended to deal with access blocks. In addition, EDs have introduced various strategies such as “fast tracking”, “enhanced triage” and new models of care such as introducing nurse practitioners aimed at improving throughput. However, most of these practices require additional resources. Some researchers attempted to optimise the resources using various optimisation models to ensure best utilisation of resources to improve patient flow. However, not all modelling approaches are suitable for all situations and there is no critical review of optimisation models used in hospital EDs. The aim of this article is to review various analytical models utilised to optimise ED resources for improved patient flow and highlight benefits and limitations of these models. A range of modelling techniques including agent-based modelling and simulation, discrete-event simulation, queuing models, simulation optimisation and mathematical modelling have been reviewed. The analysis revealed that every modelling approach and optimisation technique has some advantages and disadvantages and their application is also guided by the objectives. The complexity, interrelationships and variability of ED-related variables make the application of standard modelling techniques difficult. However, these models can be used to identify sources of flow obstruction and to identify areas where investments in additional resources are likely to have most benefit.

Keywords Optimisation · Emergency departments · Patient flow · Simulation · DES · ABMS

Introduction

Adequate health care is a basic need for every citizen of a country, and emergency department is a critical part of the hospitals. Therefore, a separate ED is usually designed in most of the hospitals to provide the necessary emergency care to the patients in need. As the population increases, the demand of emergency care also increases in almost every country of the world (Derlet 2002). Sometimes, many non-emergency patients turn up into the EDs mainly due to the lack of primary healthcare services and lack of proper

awareness of the purpose of emergency services (Al Owad et al. 2014). As a result, the EDs are getting busier day by day (Lowthian et al. 2011). On the other hand, these EDs are on constant pressure due to the budget constraints and additional regulations from governments. Healthcare sector in every country is very sensitive, and it plays an important role in national politics. So, any deviation from the desired healthcare service may create additional pressure on the healthcare professionals. Considering all these issues, the EDs are constantly trying to improve their services and so optimisation of the ED resources is one of the efficient ways to achieve that goal.

Hospital emergency departments (EDs) are very complex systems consisting of high capital intensive but limited resources such as beds, physicians, nurses, laboratories and imaging facilities. The stochastic nature of most of these resources has made the system more complex and volatile (Abo-Hamad 2011). Due to the limitation of these resources,

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most EDs are facing the problem of overcrowding of patients and long waiting times (Moskop et al. 2009). The overflow of patients affects not only the ED performance but also the patients' satisfaction and quality of care (Ahsan et al. 2019; Pines et al. 2008). But due to lack of proper integration of resources and the management of those resources, the EDs may fail to deliver the desired service to the patients (Al Owad et al. 2018; Daldoul et al. 2015). As EDs are designed to serve the patients who need immediate care and treatment, the failure may mean to leave the patients' lives in danger. Therefore, to improve the patient flow as well as to minimise the overcrowding and delays in the EDs, researchers from different areas have been working for long and some researchers recommend optimisation of the resources as a good option to solve this problem (Uriarte et al. 2015). Optimised utilisation of necessary resources is vital to achieve the desired service level.

This paper is aimed to review and systematically discuss the relevant articles which attempted to optimise ED resources for the improvement of patient flow. This review focuses on the ED resources considered in optimisation and the methods applied in the optimisation studies. From this judgemental discussion, strengths and weaknesses of the optimisation models are revealed in this paper. It is expected that this paper would help the researchers in the healthcare industries by providing an understanding of optimisation of ED resources as well as selection of right optimisation model for particular ED problems. Moreover, the researchers and the healthcare professionals will also be benefitted by having a guideline for future works.

Methodology

It is essential to perform the review process in a comprehensive and systematic way. Therefore, to prepare this review, a number of steps have been followed which are important to make the review task efficient and comprehensive. In the first step, several searching techniques and databases have been used to find some relevant literature. This searching has been performed in a scholarly search engine and in some specific databases. The databases searched here are mainly Scopus, ABI/Inform and Web of Science, because majority of the articles relevant to the focused area are available in these databases. To search some other articles, Google Scholar has been also utilised to facilitate the searching task. By using appropriate keywords such as “emergency department”, “resource optimisation”, “model”, “simulation” and “performance” and different searching tools, a large pool of literature has been obtained. But from this collection, only a few papers were found to be relevant to this focused area. Therefore, it is needed to proceed with the second step, which is the evaluation of these articles.

In the evaluation step, a preliminary evaluation was performed from the titles of the articles. Different filters have been used to avoid any duplication or redundancy. After getting rid of some duplicate and redundant articles, the abstracts and conclusions of those articles have been skimmed through to find out which are relevant and significant according to the requirements. Based on this scanning, the full texts are then read through review purpose. Different inclusion or exclusion criteria have also been used to make this evaluation easier and quicker. As a result, the huge pool of literature is narrowed down to a few good articles. Later, these articles have been reviewed carefully to investigate what they have done and how they have achieved their targets.

The overall database searching and screening process is presented in Fig. 1. This figure clearly shows the step-by-step process of searching the papers and the elimination of irrelevant articles from the search results. After having an appropriate collection of articles, these have been studied, analysed, compared and summarised.

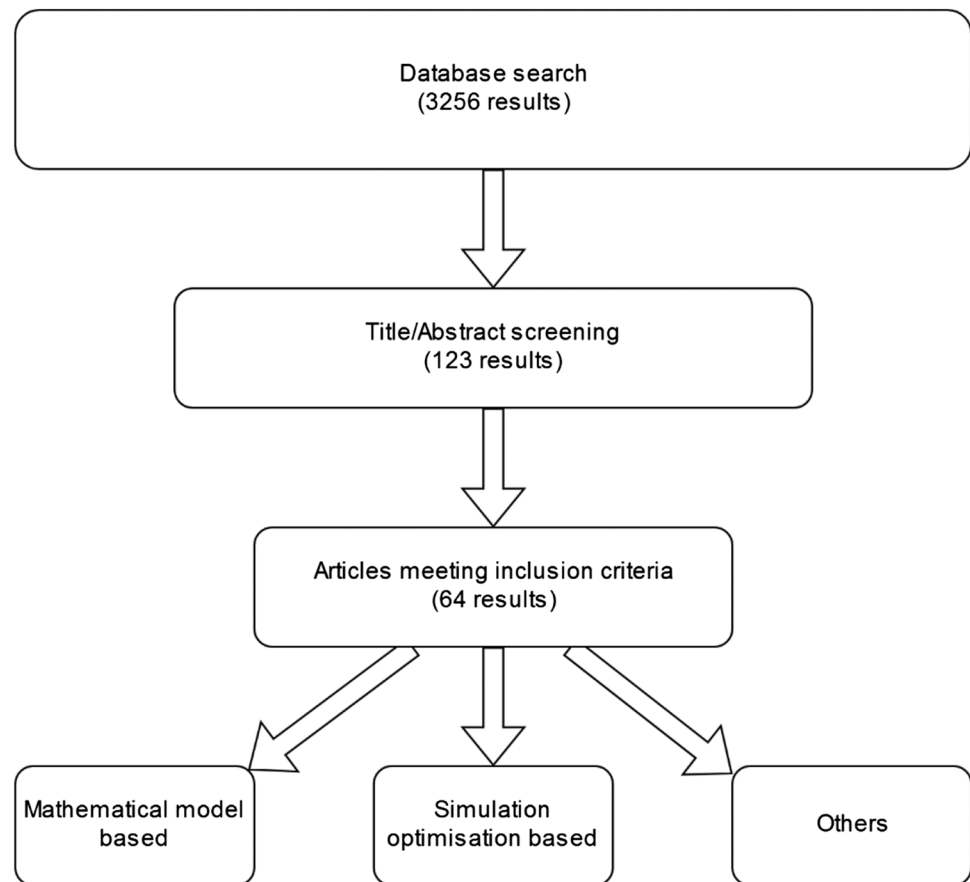
In this review paper, a total of 64 important articles were reviewed and cited which were published mostly in various highly reputed journals and covered original research works and some case studies. Among these 64 articles, it was found that approximately 42% of the studies related to ED resource optimisation were conducted in Europe, mainly in UK, France, Spain and Sweden. A large number of studies were performed in Australia and North America, and the remaining were conducted in Asia. Out of 64 articles, 51 were journal articles, nine conference proceedings, two of these and two books (Table 1). Among the journal papers, most ($31 + 12 = 43$) were high-quality Q1 (first quartile in the field) or Q1 papers (Table 2). Only nine papers are Q3, Q4 and non-ranked papers.

In terms of publication area, 44% articles reviewed here were published in emergency- and healthcare-related journals, 22% were published in various simulation journals and conference proceedings and the remaining were from operations research, production management, business management and some other multidisciplinary journals. However, majority of these optimisation works were performed by the researchers from engineering or mathematical background. It is interesting that although ED problem is a healthcare research, the number of healthcare professionals involved was not significant.

Problems in emergency departments

The healthcare industries face numerous challenges, and one of the most crucial areas is the EDs of hospitals. Major problems in ED are patient overcrowding, lack of resources, lack of right skill sets and training, inadequate



Fig. 1 Database searching and screening results**Table 1** Publication category

Publication category	No. of papers
Journal	51
Conference proceedings	9
Thesis	2
Book	2
Total	64

Table 2 Journal quality

Journal ranking	No. of papers
Q1	31
Q2	12
Q3	2
Q4	1
N/A	5
Total	51

equipment, inefficient processes and delays in attending to patients (McHugh et al. 2011; Oddoye et al. 2009). Thus, EDs are possibly considered as most challenged parts of the healthcare system. Moreover, the number of elderly

patients has been increasing day by day in the emergency departments. They need to get admitted more frequently, and they consume more resources as compared to the young patients. Though EDs are usually designed for all types of patients, the presence of increased elderly patients affects the average length of stay (LOS) (Fishman et al. 2018; Salvi et al. 2007).

Therefore, detailed studies are essential to understand and deal with long waiting time problem as well as to overcome the access block in any healthcare organisation.

The overcrowding in ED is a major barrier for providing on time emergency care, and therefore, the elimination or minimisation of ED overcrowding is a big concern and is a great challenge for emergency health services. Asplin et al. (2003) developed an “input–throughput–output” model, as shown in Fig. 2, to investigate how the receiving, treatment and discharge of ED patients are performed. This model has divided the total system into three different areas—input, throughput and output. The input segment shows the sources of incoming patients into the system; the throughput segment depicts the steps involved in the treatment process; and finally, the output segment shows different discharge patterns. This model helps in understanding the approaches of dealing with incoming and outgoing patients through ED.



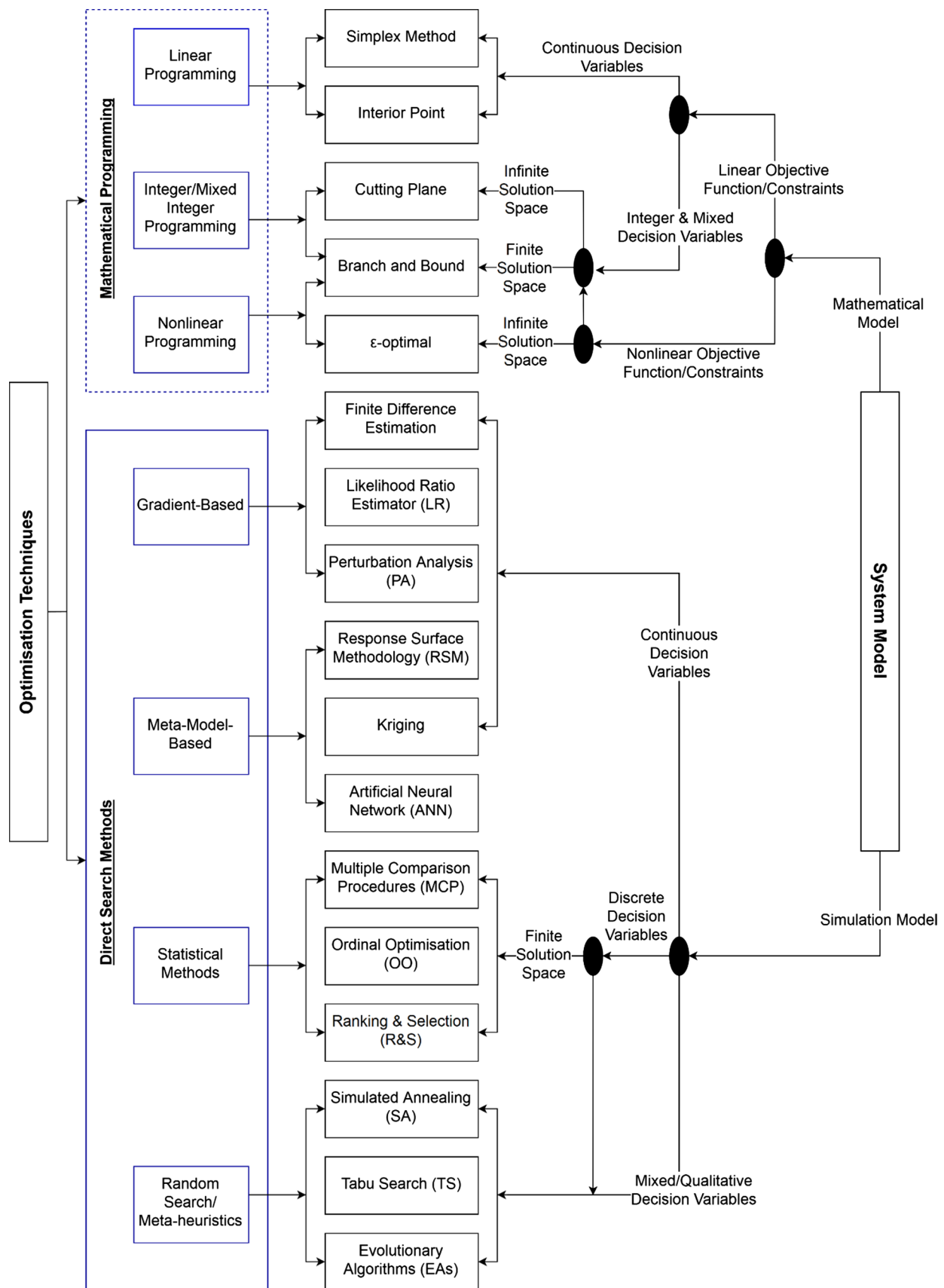


Fig. 3 Optimisation technique map (OTM) (Abo-Hamad 2011)



programming. In their map, four types of methods were considered—(1) direct search such as gradient-based method, (2) meta-model-based, (3) statistical methods and (4) random search methods. On the other hand, linear programming, integer or mixed-integer linear programming and nonlinear programming were grouped under mathematical programming. Every method can utilise various algorithms, analysis approaches and the decision variables, and the solution space may vary for each method.

In the following subsections, major modelling approaches used for ED optimisation have been critically reviewed and their findings and advantages and limitations are analysed.

Discrete-event simulation

A discrete-event simulation (DES) is generally used for modelling the operation of a system, which is considered as discrete in nature over time. Every event takes place at a specific instance in time, and a state change is marked in that system. It is assumed that there will be no change in the system in between the events and therefore the simulation is able to jump directly in time from one event to the next one.

Ghanes et al. (2014) proposed a discrete-event simulation (DES) model for understanding the ED system behaviour and improving the ED performances. They adopted a simulation-based optimisation algorithm for minimising the average LOS with a limited budget. In their model, the arrivals were assumed to follow a non-homogenous Poisson distribution which is fairly typical in majority of EDs around the world. Monday is considered as the busiest day, and most of the ED presentations are observed between 10 am and 10 pm for any day. They modelled the arrivals by considering the average arrival rate (λ_t) for each hour of a day, which is shown in Fig. 4. To validate the model, they compared the output with historical data, which were judged by experts.

Their stochastic model which was solved by simulation optimisation yielded a choice of 10% increase in staffing budget resulting 33% reduction of the average LOS. This ED model can be very helpful in configuring the ED staff.

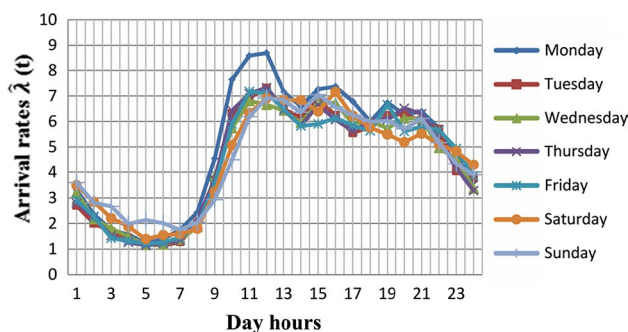


Fig. 4 Estimated hourly patients' arrival rate (λ_t) per day (Ghanes et al. 2014)

The sensitivity analysis may help the decision-makers to have a better insight on the relationship between the budget change and system performance. However, they considered routing probabilities and ED processing times as a function of patients' severity which may vary according to the patients' ages or the medical conditions.

To avoid model complexity and requirement of large amount of data collection, Ceglowski et al. (2007) described a unique approach of simulation by combining data mining with the discrete-event simulation. They used descriptive statistics combined with parametric and non-parametric methods to provide a non-intuitive grouping of variables in the data set. They reformulated the ED simulation problem by changing the focus from LOS reduction to treatment support where data mining helped in grouping the patients by treatment similarity. They proposed some adjustments in bed-changing staff to reduce the ED-toward transfer times which will eventually help in better utilisation of ED beds. However, this model considered the ED staffing as a main focus ignoring other non-human resources.

Uriarte et al. (2015) used DES with simulation-based multi-objective optimisation (SMO) technique. They simulated mainly the patients, wards and beds, resident and intern physicians, the receptionist, triage nurses, ambulance nurses and registered nurses (RNs), laboratory and X-ray staff in order to find the best ED configuration to reach the desired level of time to first meeting with doctor (TMD) and LOS. In addition, they minimised the number of physicians and beds and the several processing times for physicians by using a robust algorithm, namely non-dominated sorted genetic algorithm (NSGA-II). The number of nurses and their working procedure were not taken into consideration, which is a major weakness of the model. Moreover, this research mainly focuses on the simulation human resources without considering non-human resources and the real-world ED factors which are relevant to resource optimisation.

Zeinali et al. (2015) developed a DES model with an appropriate meta-model to support the decision-making in the ED. This model acts as a decision support system (DSS) by helping in optimisation of receptionist staff, nurses, resident doctors and beds. Their meta-model selection process is depicted in Fig. 5. They analysed response surface methods, radial basis functions and neural networks as candidate meta-models.

Zeinali et al. (2015) also proposed a meta-model-based DSS, which is shown in Fig. 6, and this is a useful tool for different strategic planning and operational management procedures. Their proposed model may help in minimising the total average waiting times of patients. They claim that in the experimental study, they obtained about 48% reduction of total waiting time. However, not much detail was provided about the model and experimental procedures.



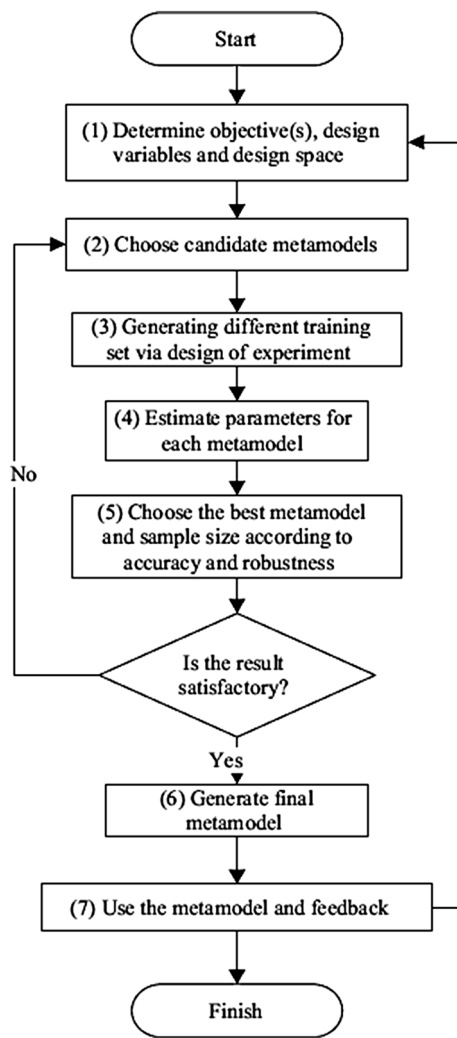


Fig. 5 Meta-model selection process chart for ED resource optimisation (Zeinali et al. 2015)

Some studies aimed at optimising patient flow in EDs while minimising associated costs (Memari et al. 2016; Ahalt et al. 2018). Memari et al. (2016) combined DES with queuing theory to develop the model. Eventually, a modified genetic algorithm was developed to optimise different stages of the ED.

DES is one of the most widely used approaches to study and analyse EDs, and due to its efficiency and appropriateness, different simulation packages for EDs are developed based on this modelling concept. However, DES models mostly targeted human resources in the optimisations and therefore application of this method will be difficult and time-consuming where more resources are involved. Therefore, selection of this model is dependent on the requirements and situations of the system.

Agent-based modelling and simulation (ABMS)

Agent-based models (ABM) are generally used to simulate the actions and interactions of independent agents, such as people, groups and organisations, to evaluate their impacts on system. Several research works have been found in the literature which applied ABMS in ED. Cabrera et al. (2012a) presented an ABMS to design a DSS for ED performance improvement. They mainly tried to optimise the ED staff, such as doctors, triage nurse and admission staff considering the problem as a multi-dimensional and multi-objective. They used **NetLogo** programmable modelling environment for simulating natural and social phenomena and proposed a new index to minimise the LOS of ED patients.

Ajmi et al. (2019) developed an orchestration architecture that simulates the patient's pathway workflow in real time. A multi-agent system through dynamic optimisation was used to confirm the coordination between the medical staff to improve the patient care. They considered three performance indicators, namely the remaining patient care load (RPCL) for estimating what remains in care within the complete patient care process, the cumulative waiting time (CWT) and the LOS in their model. Yousefi and Yousefi (2019) performed a similar investigation to ensure the appropriate staff allocation in ED to minimise the “door-to-doctor” time considering the capacity and budget constraint. Cabrera et al. (2012a) also applied an ABMS to develop a DSS for the ED operation aiming to help the ED managers in developing strategies and management guidelines in order to decrease patients' waiting time and to improve patient throughput (Cabrera et al. 2011, 2012b). A significant improvement was reported though the optimisation was limited to staff only. Some limitations were observed including the dropping off execution speed if the number of agents is large in ABMS while analysing a complex system. Though human resource is the most important resource in every ED, there are many non-human resources which significantly affect the ED patient flow, which were neglected in these studies.

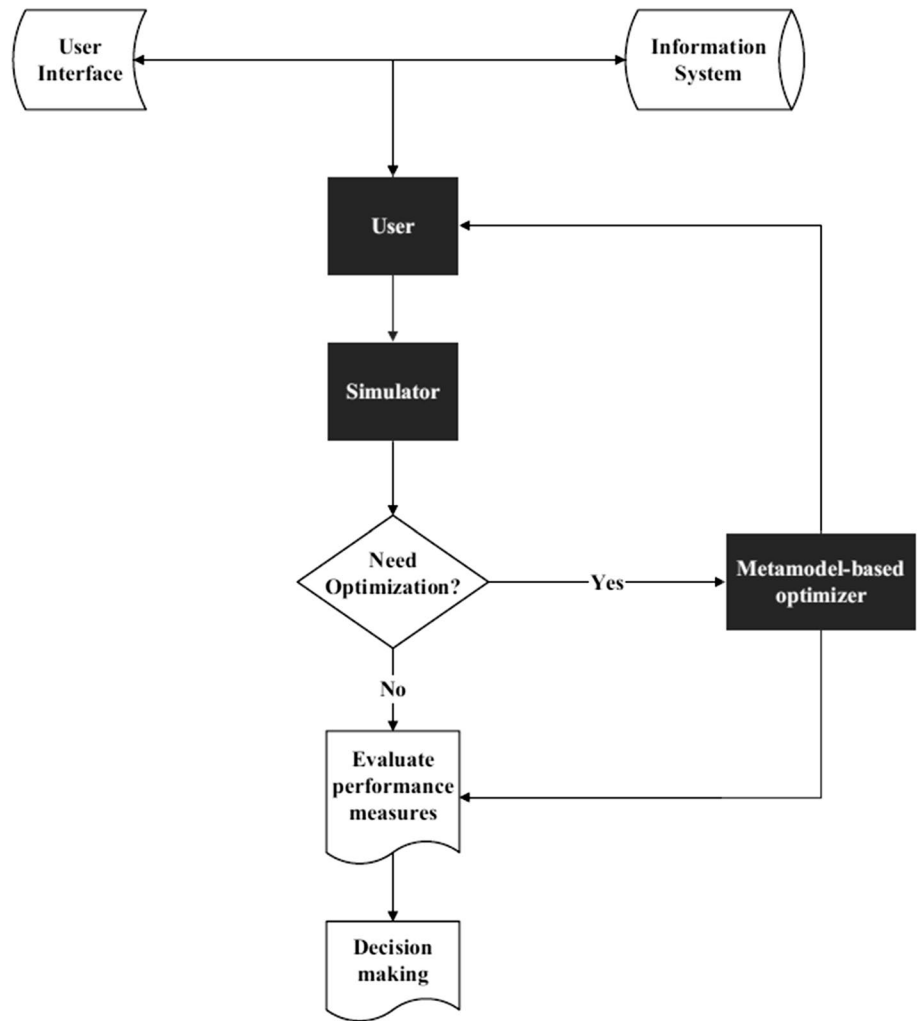
Mathematical modelling

As healthcare system is integrated with many functional units and parts, there is an increased demand for modelling methods that account for patient care pathways and interactions between patients and their environment (Lim et al. 2012). For example, an evaluation of a computed tomography (CT) scanner in accurate diagnosis resulted in huge demand for these equipments in hospitals. Any modelling approach, therefore, needs to consider the current and increased demand of these machines and how that may affect service in other areas of the hospital.

Systems analysis techniques have been developed over decades in the operations research and industrial engineering



Fig. 6 Meta-model-based decision support system (Zeinali et al. 2015)



fields. Under systems analysis, mathematical modelling techniques involve describing a system or process from the real world using a set of variables and equations. These models have been identified for use in health technology assessment, mainly because they allow decision-makers to simulate hypothetical scenarios without making actual changes to the system. Such models enable the analysis of “what-if scenarios” and provide the opportunity to identify optimised solutions under constraints (e.g. resources, budget, and benchmarks). Measures of systems behaviour include waiting time, throughput and resource utilisation where waiting times are of particular interest due to the pressure from the public to receive timely care.

Lim et al. (2012) tried to optimise the number of human and material resources of ED and proposed a mixed-integer linear programming (MILP) method that minimises the number of waiting patients. They simultaneously considered four patients’ queue. To solve this model, they use the solver ILOG CPLEX Optimisation Studio. The programme has been tested on a set of instances. Numerical results show

that the number of waiting patients can be decreased by optimising the number of the human and material resources (Daldoul et al. 2015; Jafari and Salmasi 2015).

As ED is considered as a complex system with limited resources and arbitrary demands, researchers tried to optimise both the human and non-human resources by using mathematical programming. Daldoul et al. (2015) proposed a mixed-integer linear programming (MILP) to minimise the number of patients waiting. They considered four individual queues of ED patients simultaneously—two assessment queues of patients before and after having preliminary examination by physicians, one queue after seen by nurse, and the fourth one waiting for beds. Their programming suggested a decrease in the number of patients waiting due to the optimisation of resources. However, they did not consider the uncertainty with the patients’ arrival into consideration also ignored the complex relationship between the resources in ED operations.

Kwak and Lee (1997) utilised a linear goal programming model to direct decision-making of staff scheduling in a



hospital. Goal programming was applied with the assistance of computer program to find out a satisfactory solution to human resource scheduling problem. That study involved 36 variables and 14 constraints, and the goal programming model helped in identifying the solution in an efficient way. Similar investigations were also performed by Svirsko et al. (2019) and Mohammadian et al. (2019). However, complexity of these models may discourage the healthcare professionals to use this in ED staff scheduling situation. Moreover, their study was limited to staff scheduling only, whereas every healthcare system, especially the EDs, is comprised of lots of valuable non-human resources which require proper utilisation.

Some mathematical models are also developed for medical diagnosis in the ED. Selker et al. (1995) used logistic regression, classification trees and neural networks to predict usage of medical devices. This model can provide outstanding performance and help in making some clinical decisions and also to develop policy. Though mathematical modelling can simplify a complex situation, sometimes it is difficult to integrate all the aspects of the real problems in the developed model. Adequate knowledge and relevant experience are highly needed to the successful utilisation of mathematical models.

Queuing model

Queuing models are different types of mathematical models which are mainly used to predict the queue lengths and waiting time. Omar et al. (2015) focused on human resources of an ED and tried to find out a best mix of service quality and working conditions. They worked with the staff scheduling to optimise the shift among staff and to decrease patients' waiting times. By approximating the appropriate waiting times of patients, they proposed a stochastic mixed-integer programming model and solved the model using a sample average approximation (SAA) approach. They also performed the numerical experiments by using the data from a French hospital for comparing various staff scheduling strategies (Omar et al. 2015). Their model delivered effective scheduling solutions for ED staff. The validity of assumptions and robustness of solutions were positively verified by a discrete-event simulation model. However, they approximated the patients' service times with exponential distribution which are usually not the case in real-life situations.

Hu et al. (2018) and Zhang et al. (2019) also utilised queuing theory to model the ED patient flow. They developed some priority criteria by which the patients will be served in the ED. They focused mainly on the application of queuing theory in simulation model to develop the realistic ED patients flow pattern. It was observed from their studies that this priority helps in managing non-emergency patients. However, the overall improvement in patient flow

for all other patients was not that significant. Wiler et al. (2013) and Vass and Szabo (2015) worked with queuing models to solve the waiting time problems in the ED and also to decrease the number of patients left without being seen (LWBS). This model has been widely used as an integral part of other simulation models, but as a standalone tool, this model is not always effective.

Simulation optimisation

Several simulation optimisation approaches have been used to solve ED problems. Ibrahim et al. (2015) proposed a simulation optimisation model framework for studying ED operations and problems and finding out their solutions. It is expected that integrating simulation with optimisation can aid the management in decision-making process about resource allocation. Ambulance diversion (AD) was reported as a critical issue to have potential damaging impact on lengthy transport. Ramirez-Nafarrate et al. (2011) proposed a simulation optimisation approach for identifying suitable parameters of ambulance diversion, and a significant improvement was observed in patient flow in the overall system. However, the outcome of the model depends on the ambulance diversion policy applied to a particular ED and also on the destination policy which is associated with the diversion strategy.

Ahmed and Alkhamis (2009) utilised a simulation model for designing an optimised decision support tool for a government hospital ED in Kuwait. They tried to estimate the effect of number of staff at various levels on efficiency of service. According to their results, with the existing hospital resources, the simulation optimisation model provided optimal staff distribution resulting in 28% improvement of patient throughput and 40% decrease in patients' waiting time. Their optimisation model was limited to the staffing of the ED only as other resources were not considered.

A data-integrated simulation-based optimisation for engaging nurses to admit patients has been found in other studies (Sundaramoorthi et al. 2010; Wong et al. 2014; Stefanini et al. 2018). A heuristic policy has been used for assigning new admission to the nurse and a partially optimised policy for minimising the variation of workload among nurses during the whole shift.

Diefenbach and Kozan (2011) and Chen and Wang (2016) analysed the patient flow in ED and optimised the patient flow using simulation optimisation. The performance of the ED was improved substantially by balancing the utilisation of doctors, treatment areas and critical bed levels. They utilised several operations research tools to analyse and solve the problem. Their simulation results show a substantial improvement of ED performance by optimising a number of parameters.



Weng et al. (2011), Feng et al. (2015) and Rabbani et al. (2018) developed models to determine an optimal use of ED resources considering actual situation of waiting times and system times of ED patients. It was reported that significant improvement was made in LOS by using their simulation optimisation. Similar simulation models were developed other researchers using multi-criteria decision-making (MCDM) method to evaluate the ED performance (Abo-Hamad and Arisha 2013; Hsieh et al. 2018; Eskandari et al. 2011; Kuo et al. 2016; Peck and Kim 2010; Yeh and Lin 2007). Some of the simulation models were developed based on the data available from the hospital systems; however, the real-life applications of those models are quite difficult due to some complexity of the data processing.

A comparative summary of some of the important papers reviewed in terms of the findings and advantages/limitations is given in Table 3 for easy understanding.

Emergency department efficiency

ED patient care efficiency is a vital factor for the quality of care as well as performance of the healthcare system. Many research works have been conducted to address ED patient care efficiency. Kyriacou et al. (1999) aimed in calculating the time intervals in the main ED patient care in order to identify the underperforming areas and their effect on ED. They also targeted to measure the impact of inpatient bed availability on patient flow and to quantitatively measure the impact of administrative interventions.

Zhao et al. (2015) used design of experiments (DOE) in simulation modelling and developed an approach to detect bottleneck of the system. They studied an ED for their modelling and successfully detected the bottleneck with an efficient time-saving way. They also utilised benchmarking with the DOE to get better results and showed the patient flow improvement. Kuo et al. (2016) presented a case study to analyse ED patient flow by using simulation. They built a simulation model by using ARENA, discrete-event simulation software, to explain the main activities in ED. They proposed a simulation optimisation approach, integrated with meta-heuristics, to get a better estimation of parameters. This simulation model helped in evaluating the effect of probable variations to the system by considering different circumstances.

Joubert et al. (2015), De Freitas et al. (2018) and Oyedokun et al. (2019) introduced lean manufacturing concept in health care and discussed the effect of employing a physician in triage to improve the ED efficiency. They showed that triage physicians influence “low-severity” patients LOS significantly but they do not affect acute patients.

The efficiency of ED depends not only on the ED operations itself, it is also related to the entire hospital

management systems. The successful development of ED optimisation model can improve the ED efficiency, but all the activities responsible in delaying the ED services need to be identified and considered properly.

Discussion

As there is no evidence of any article on the review of the literature on optimisation of ED resources has been reported, this paper should be a valuable source for the researchers in the relevant field. From this review, it is found that there are several methods available to optimise the ED resources including mathematical modelling, discrete-event simulation, agent-based modelling, genetic algorithm-based optimisation and so on. Each method has its own advantages and limitations, and different methods are suitable for different problem scenarios.

It is found that DES model has been used for improving the ED performance by optimising the ED resources such as number of physicians, nurses, beds and other staff. The performance is characterised by ED LOS or waiting time or cost. To solve the optimisation problem, different algorithms have been used including genetic algorithm. Sometimes, DES model is combined with other methods to get better result such as data mining or any meta-model to use as DSS tool (Ceglowski et al. 2007; Ghanes et al. 2014; Memari et al. 2016; Uriarte et al. 2015; Zeinali et al. 2015). On the other hand, ABMS is mainly used for developing a DSS tool by optimising the human resources. It is also a popular method for its cost–benefit and time advantage (Cabrera et al. 2011, 2012a, b).

Different mathematical models such as queuing theory can be used based on the system requirements. The selection of appropriate mathematics and solution approach will influence the accuracy of the result.

There is no single model which considered all the human and non-human resources, and it is not always feasible to bring everything under consideration. Therefore, it is very important to recognise first which resources are critical for required service performance and how much impact those resources may contribute in achieving the target performance.

It can be noticed that some hospitals cannot perform according to their resource strengths and the same overcrowding and longer waiting times may result only because of lack of optimum use of available resources. In those cases, implementation of lean philosophy can assist in eliminating wastes by avoiding non-value-added activities and the successful implementation of lean concept requires successful identification of sources of wastes and appropriate lean tool uses (Dickson et al. 2009; Rutman et al. 2015). Therefore, while optimising ED resources, it is also important



Table 3 Summary of some major articles

Study	Year	Modelling approach	Resources considered	Geo-graphical location	Findings	Comments/limitations
Ghanes et al. (2014)	2014	DES	Doctors and nurses	France	10% increase in current staffing budget reduces the average LOS by 33%	The model was developed for some human resources only and aimed for LOS improvement
Uriarte et al. (2015)	2015	DES	Doctors and beds	Sweden	Patients' waiting time to meet a physician reduced by 30-min and 50-min reduction in LOS	Nursing activities were ignored
Zeinali et al. (2015)	2015	DES	Receptionists, nurses, doctors and beds	Iran	The total average waiting times of patients decreased by 48% with the meta-model-based optimisation	Developed only for the Chest Pain Unit, not the whole ED
Memari et al. (2016)	2016	DES	Doctors and nurses	USA	Queuing model is faster and easier for simple ED, whereas DES is more suitable for comparatively complex ED.	Compared only the effects of the optimisation on ED performance by simulating simple to complex situations. However, no real data were utilised
Cabrera et al. (2012b)	2012	ABMS	Doctors, triage nurses and admission personnel	Spain	Proposed an index to reduce the LOS in ED	Based on the human resources only, no specific result was shown
Daldoul et al. (2015)	2015	Mathematical modelling	Doctors, nurses and beds	Tunisia	Proposed a mixed-integer linear programming to optimise the number of doctors, nurses and beds so that the number of patients waiting in ED can be minimised	Uncertainties with the arrival of patients were ignored
Omar et al. (2015)	2015	Queuing model	Doctors and nurses	France	Proposed a stochastic mixed-integer programming to optimise the scheduling of doctors and nurses and showed the number of patients at the different time of the day with the varying staff	Limited to staff scheduling
Ahmed and Alkhamis (2009)	2009	Simulation optimisation	Doctors, lab technicians and nurses	Kuwait	Presented an optimised staffing level to improve the patient throughput by 28% and to reduce the patients' waiting time by 40%	Limited to staffing only
Diefenbach (2010)	2010	Simulation optimisation	Doctors and beds	Australia	The number of doctors and beds is not synchronised, and by swapping the doctors from one shift to another, the performance can be increased by 60%. Moreover, the overflow beds can be opened based on the number of patients waiting	Nursing staff were not taken into consideration for modelling
Chen and Wang (2016)	2016	Simulation optimisation	Doctors, nurses, X-ray machines, CT scanners, laboratories, beds	Taiwan	The proposed integrated algorithm helps in identifying the allocation of resources with the minimisation of average LOS	The utilisation of resources was not described accordingly



to consider lean philosophy so that the optimised ED solution can ensure the maximised utilisation of all the available resources.

It is noteworthy to mention that every ED is different in terms of the target patients, available resources and management practices. However, the major operational functions of most of the EDs are almost similar. So, the optimisation of resources may help every ED to provide the best service and to ensure the best utilisation of resources. The papers reviewed in this paper demonstrate how the ED resources can be optimised using different methods and it is understandable that not all the methods are appropriate for every ED. The selection of ED resources which need to be optimised and method which can be used for optimisation are critical, and this paper will guide in determining the appropriate optimisation approach.

In summary, optimisation of ED resources is highly beneficial for the improvement of ED performance and its patient flow. However, all the research found in the literature attempted to optimise some of the resources only. For example, most researches considered the human resources only in their optimisation and some others considered the non-human resources including the number of beds, imaging equipment, etc. To get an efficient optimisation outcome, entire range of resources needs to be studied and prioritised. Future studies with better modelling approaches and competent optimisation techniques with faster solving procedures are needed.

Conclusion and future research direction

The necessity of ED resource optimisation has been realised by the ED professionals, but lack of adequate knowledge on appropriate optimisation techniques may act as a barrier in utilisation these techniques. For every emergency department, the performance is measured by a number of indicators and the patient flow is directly related to these indicators. Therefore, many investigations have been conducted in the healthcare systems by utilising various operations research tools and operations management strategies. Every technique has its own strengths and weaknesses, and this paper attempted to extract these by critically reviewing them. The reviewed literature in this paper demonstrates how different approaches are applied to improve the ED performance by optimising both the human and non-human resources.

Successful implementation of ED resource optimisation techniques relies on the consideration of the appropriate decision variables and resource constraints. Due to the ineffective application of optimisation tool, the desirable outcomes might not be achieved. Therefore, while optimising the ED resources, it is highly needed to identify the decision

variables carefully and develop the model appropriately so that the objective can be reasonably achieved. Moreover, lean philosophy can be incorporated in future studies so that the optimised result can be adopted in a waste-free system.

Existing studies reveal that various optimisation techniques were used to improve the ED performance. However, most studies primarily considered human resources in their optimisation and therefore non-human resources are largely ignored. These non-human resources significantly affect ED and other hospital services and therefore must be adequately considered in any modelling. Impact of adopting new technology and equipment (e.g. tomography sensors) has not been considered in any of these studies, which is a critical miss out in these studies. Therefore, further studies are required overcome these limitations and take a holistic approach. Also future studies can consider integrating lean philosophy in the optimisation process to facilitate removing wastes before resource optimisation. Though this paper mainly has discussed the analytical and tactical aspects of various optimisation models, the financial implication has not been adequately reviewed.

This paper will help the researchers in selecting the right optimisation approach for their desired goals and in predicting the results.

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