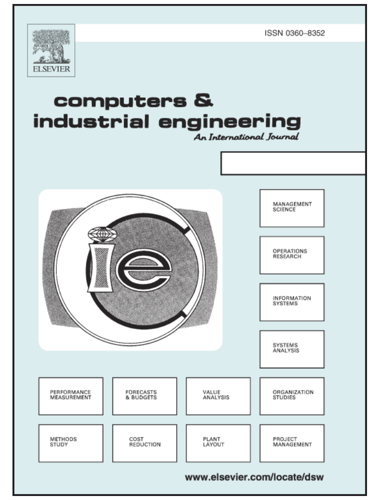
# Simulation of emergency department operations: a comprehensive review of KPIs and operational improvements

Peer-reviewed author version

VANBRABANT, Lien; BRAEKERS, Kris; RAMAEKERS, Katrien & VAN NIEUWENHUYSE, Inneke (2019) Simulation of emergency department operations: a comprehensive review of KPIs and operational improvements. In: Computers & industrial engineering, 131, p. 356-381.

DOI: 10.1016/j.cie.2019.03.025
Handle: http://hdl.handle.net/1942/28197

Accepted Manuscript




# Simulation of emergency department operations: a comprehensive review of KPIs and operational improvements

Lien Vanbrabant, Kris Braekers, Katrien Ramaekers, Inneke Van Nieuwenhuyse

PII: S0360-8352(19)30161-5
DOI: https://doi.org/10.1016/j.cie.2019.03.025
Reference: CAIE 5761

To appear in: *Computers & Industrial Engineering*

Received Date: 5 December 2017
Revised Date: 21 December 2018
Accepted Date: 10 March 2019

Please cite this article as: Vanbrabant, L., Braekers, K., Ramaekers, K., Nieuwenhuyse, I.V., Simulation of emergency department operations: a comprehensive review of KPIs and operational improvements, *Computers & Industrial Engineering* (2019), doi: https://doi.org/10.1016/j.cie.2019.03.025

# Simulation of emergency department operations: a comprehensive review of KPIs and operational improvements

Lien Vanbrabant[a,b,*], Kris Braekers[a], Katrien Ramaekers[a], Inneke Van Nieuwenhuyse[a]

[a] *UHasselt, Research Group Logistics, Agoralaan, 3590 Diepenbeek, Belgium*
[b] *Research Foundation Flanders (FWO), Egmontstraat 5, 1000 Brussel, Belgium*



*Corresponding author

*Email addresses:* lien.vanbrabant@uhasselt.be (Lien Vanbrabant), kris.braekers@uhasselt.be (Kris Braekers), katrien.ramaekers@uhasselt.be (Katrien Ramaekers), inneke.vannieuwenhuyse@uhasselt.be (Inneke Van Nieuwenhuyse)

# Simulation of emergency department operations: a comprehensive review of KPIs and operational improvements

**Abstract**

Emergency departments (EDs) are one of the main entry points of a hospital, offering non-stop healthcare services to patients with various needs. ED crowding is considered a major international problem. To cope with this problem, operations research techniques have been widely applied to analyse and optimise ED operations. In this regard, two essential aspects are the key performance indicators (KPIs) and improvement options under investigation. This paper structures the scientific literature on ED simulation based on KPIs and improvement options. Apart from a comprehensive discussion of individual KPIs and individual improvement options, studies combining multiple KPIs or multiple improvement options are discussed. In addition, the two aspects are linked by investigating the relationship between KPIs and improvement options. The focus is on simulation research, as this technique is most suitable to capture the randomness and complexity of patient flow through the ED. Because of the importance of efficient ED operations and the general recognition, and worsening, of the crowding problem, the amount of research keeps expanding. Structuring the literature can provide guidance to both researchers and practitioners when deciding on the KPIs and improvement options to consider. In fact, this study is the first to comprehensively analyse the relations between KPIs and improvement options, thereby providing insights into which options have an effect (either positive or negative) on which KPIs according to current literature. Finally, this literature review reveals promising areas for future research into ED crowding.

*Keywords:* Emergency department, Patient flow, Simulation, Review, Key Performance Indicators, Operational improvements

## 1. Introduction

### *1.1. Background*

Emergency Departments (EDs) constitute an important component in a healthcare system. They are one of the main entry points of a hospital, offering non-stop healthcare services to patients with various needs. From a social point of view, clearly it is crucial that EDs work efficiently, since timely and good services can save lives [8]. However, EDs are large, complex and dynamic units which are difficult to manage. Moreover, EDs are confronted with a substantial growth in demand due to the ageing population and the trend towards utilising the ED for non-emergency care [18, 42]. In Belgium, the number of ED visits increased at a yearly rate of 5% between 2008 and 2015, and is expected to increase even further. Other European countries, such as France, the UK, Germany and the Netherlands, as well as the United States, have experienced a similar growth in the demand for emergency care [12, 125]. Combined with the ever tightening budgets, this has led to the problem of (over)crowding in many EDs. Crowding occurs when the demand for emergency services exceeds the available resources in the ED [2, 61].

Currently, ED crowding is considered a major international problem. It has significant consequences for both patients and caregivers, as well as the entire hospital. A lack of sufficient resources prevents timely and suitable services, leading to an increased length of stay of patients, increased waiting times, patient dissatisfaction, an increased probability of patients leaving the ED without treatment, bad patient outcomes, etc. [61, 80, 100, 99, 103]. Caregivers suffer from high utilisation rates, causing high stress levels, decreased morale and productivity, miscommunication and medical errors [99, 104, 103]. Finally, ED crowding has an impact on the hospital as a whole. Ambulance diversion, patients leaving the hospital without finishing their treatment and elective cancellations imply a financial loss for the hospital [61, 103, 107].

*1.2. Overview of OR/OM methods used to investigate ED operations*

To face these challenges hospital managers are continuously exploring opportunities to improve the efficiency of the ED without reducing the quality of care [4, 27]. For this purpose, operations research and operations management techniques (OR/OM) have been widely applied. These techniques are suitable to analyse and optimise processes in healthcare organisations and especially EDs [27, 112]. The OR/OM techniques used to describe and analyse patient flow in EDs can be classified in two categories according to Sinreich and Marmor [122]: prescriptive and descriptive techniques. The descriptive techniques are used to model and analyse ED operations, while prescriptive techniques focus on optimising ED performance. This section gives a brief discussion on the prescriptive and descriptive techniques used in ED literature. More comprehensive reviews on OR/OM techniques used to investigate ED performance can be found in, for example, Bhattacharjee and Ray [20], Saghafian et al. [112] and Wiler et al. [141].

Descriptive techniques can be subdivided into analytical modelling, simulation modelling and statistical/empirical modelling [20]. Analytical models consist of a set of mathematical equations that determine the relationship between system parameters and the performance of the system. In the context of EDs, queueing theory is the most prevalent analytical modelling technique. Other techniques in this category that have been applied to patient flow modelling are Markov models and fluid models [20, 39]. The simplicity and efficiency of analytical models makes them a popular method for modelling and analysing patient flow [112]. However, as analytical models mostly rely on closed-form mathematical formulations, they are not suitable to model the complex, stochastic and dynamic nature of healthcare systems without introducing simplifying assumptions. Examples of restrictive assumptions in the context of an ED are stationary arrival and service processes, state-independent service processes, no patient abandonments or system overload possible, independent process delays between separate time intervals, simplified priority rules, queueing for one server at a time, steady-state being reached quickly, limited number of performance measures, etc. [20, 39, 112, 141]. As a result, the appropriateness and suitability of analytical models depends on the type of model used, the underlying assumptions, and the goal of the study [39, 112]. If the level of detail taken into account is appropriate given the research objectives, or the problem under investigation is of moderate complexity, analytical models are very efficient to analyse patient flow and to investigate the effect of parameter changes on performance measures [20, 112].

When patient flows are highly complex, which is the case in emergency departments, analytical models are less appropriate for modelling and analysis [20]. In this case, simulation is a suitable technique. Simulation refers to a broad collection of methods and applications to imitate the behaviour of real systems [72]. Simulation is further divided into discrete-event simulation, system dynamics and agent-based modelling [99]. The main advantage of simulation is that a great level of detail can be taken into account, such as individual patient characteristics, which makes the required assumptions less restrictive. In addition, time-dependent and stochastic characteristics can be included. These characteristics make a simulation model capable of approximating real-life behaviour, and allow for reliable what-if analyses [78, 112, 122]. The extensive use of simulation in previous research to investigate ED performance and test improvement options, confirms these findings (e.g. [20, 57, 104, 112]). Although simulation is a suitable technique to investigate ED operations, the generated output is only valuable when the model closely resembles the real system. In an ED context, most simulation model components and parameters are characterised by a large amount of stochasticity (e.g. process times, arrival patterns, etc.), which necessitates the use of probability distributions to model them realistically. In this regard, accurate input data on the real system is a prerequisite for the construction of a realistic simulation model [127]. Sources of input data are, for example, electronic health records or empirically gathered data from interviews or observations. Based on sufficient and correct input data, the most suitable probability distribution can be determined. A lot of probability distributions exist, with exponential, Poisson, triangular and empirical distributions as the most used ones in ED simulation studies. An overview of probability distributions and their characteristics can be found in Kelton et al. [72] and Law [85]. Capturing ED complexity and stochasticity by means of correct probability distributions improves simulation model reliability. Apart from the large amount of input data needed, other disadvantages of simulation techniques are the time-consuming nature and the lack of generalisability [39, 122].

A third descriptive technique for modelling and analysing patient flow are statistical/empirical models. These models are entirely based on empirical data to estimate system performance and the relationship between system parameters and performance measures [20, 39]. Formula-based methods, regression-based methods and time-series analysis are statistical/empirical approaches used for ED patient flow modelling. Given the dependency on empirical data and the inherent imperfection of these modelling approaches to capture all variability in system output, their application is rare within an ED context [20, 141]. However, these methods are gaining attention as a way to extract information regarding system operations from empirical data, which then can be used as a basis for analytical or simulation modelling [20]. Evidence from empirical research can be used to enhance and facilitate simulation model construction, as it provides insights on real system behaviour. Furthermore, empirical findings may be used to narrow the focus of the study, which in turn may reduce simulation efforts. Finally, empirical research findings may provide a basis for the formulation of improvement scenarios, relevant key performance indicators (KPIs) to evaluate these scenarios, and hypotheses regarding the relationship between KPIs and improvement options.

The previously discussed OR/OM techniques are used for analysing ED performance. The second category of OR/OM techniques described by Sinreich and Marmor [122], prescriptive techniques, focus on optimising ED performance. The main technique in this category is mathematical programming. Mathematical programming describes a complex system concisely by use of an objective function and constraints. Examples of mathematical programming methods are data envelopment analysis, linear programming, integer programming and goal programming [20]. The aim is to define the values of the decision variables in the mathematical programming problem such that system performance is optimised. Both exact methods and (meta)heuristics can be used to solve mathematical programming problems, but (meta)heuristics (e.g. genetic algorithms, tabu search, local search) are mostly used as EDs are complex and finding the optimal solution may be very time-consuming and likely impossible [112].

In addition to mathematical programming, optimisation techniques may be integrated with the patient flow modelling techniques (i.e. descriptive techniques). Both techniques can be combined in an iterative way, or they can be applied in a sequential way [39]. Simulation-optimisation is the most widespread method in this category, but the application in ED research is still scarce and relatively new. Simulation-optimisation is the process of finding the best values of some system parameters, where the performance of the system is evaluated based on the output of a simulation model [4]. The main drawback of mathematical programming models is their deterministic nature, but if used in combination with simulation the stochastic nature of EDs can be taken into account. Examples of simulation-optimisation methods applied in ED studies include metamodels (e.g. [147]), metaheuristics (e.g. [32, 47, 146]) and simulation-optimisation software (e.g. OptQuest) (e.g. [52, 138]).

### *1.3. Focus and objective*

The focus of this review is on simulation studies for several reasons. First of all, the quality of research on ED operations depends on the proper selection of a representative and comprehensive set of KPIs. An ED is evaluated on the defined KPIs and based on the analysis, improvement options for the crowding problem are specified and tested. Evaluating scenarios based on multiple KPIs and simultaneously implementing a number of improvement options can be beneficial, but this is difficult in an analytical or mathematical model. Within a simulation model, the simultaneous effect of different improvements can be analysed with respect to different measures of ED performance. Secondly, an ED is characterised by its complex and stochastic nature. Based on the overview of OR/OM techniques used in an ED context (Section 1.2), it is concluded that simulation techniques are best suited for modelling and analysing EDs. The desired level of detail can be taken into account, together with the stochastic nature and queueing behaviour of EDs. Thirdly, simulation software enables visualisation of the simulation model and facilitates communication with people who are not familiar with the OR domain, for example ED staff. Finally, simulation is not only an appropriate technique for modelling and analysis, but also as a basis for system optimisation by use of simulation-optimisation techniques. Simulation-optimisation enables to take the stochastic nature of an ED into account when optimising system performance and has great flexibility in terms of system assumptions [39].

Because of the large and distinct amount of simulation literature on analysing and optimising ED operations, there is need for a structured overview to provide guidance to researchers and practitioners. In addition, structuring the literature may facilitate the identification of opportunities for future research. The last years several literature reviews have been published [51, 54, 104, 112, 114]. However, this review is fundamentally different from previous ones, as discussed below, and provides additional insights on the two essential aspects when analysing/optimising ED performance (KPIs and improvement options), as well as their relation. In fact, this study is the first to comprehensively analyse the relations between KPIs and improvement options, thereby providing insights into which options have an effect (either positive or negative) on which KPIs according to current literature. In addition, promising areas for future research are revealed.

The first part of this literature review consists of a discussion on KPIs. In order to analyse and optimise the operations of an ED, it is important to define the KPIs. Research findings are only reliable and valuable if ED performance is measured without bias, but no consensus is reached within the scientific (OR) community and within the medical world on the most appropriate KPI(s). Numerous ways to measure ED performance are provided in literature and no single measure can capture every aspect of ED performance [51, 112]. Besides, KPIs complement each other, so the adoption of a combination of KPIs is advisable [51]. As each KPI has advantages and disadvantages, the first part of this review classifies the scientific literature based on the KPIs used to measure ED performance. For each KPI, a definition, (dis)advantages, and an overview of the articles applying the specific KPI are given. In addition to a discussion of individual KPIs, combinations of them and the methods used to investigate ED operations based on a set of KPIs are identified. In 2014, Ghanes et al. [51] published a literature review on KPIs of ED operations. The current review contains a more thorough classification, as Ghanes et al. [51] only reported on four widely used KPIs, while all KPIs present in the reviewed literature are discussed in this paper. Furthermore, the review of Ghanes et al. [51] does not contain a discussion on using combinations of KPIs.

The second aspect are improvement options. Besides measuring ED performance, a researcher should decide on the improvement options considered to optimise it. Patient flow through an ED consists of multiple processes. These processes are interdependent and influenced by multiple factors, both internal and external to the ED [11]. In this complex environment, finding a solution to the crowding problem is not straightforward. As a result, a lot of improvement options are investigated in literature. The second part of this literature review consists of a comprehensive overview of the improvements examined by the scientific community. An explanation is given of each improvement option, together with an overview of the papers investigating the improvement option and their conclusion on the effectiveness to alleviate crowding. Additionally, the combinations of improvements already investigated are determined.

The third contribution of this review is the linkage of KPIs and improvement options to indicate the effect a specific improvement has on the diverse aspects of ED performance. Moreover, links that are not yet analysed or for which contradicting results are found within literature, are identified. The literature review of Saghafian et al. [112] also describes individual improvement options in the different parts of patient flow. Their review discusses all OR/OM literature on ED operations and looks at the specific OR/OM technique used to analyse ED performance and test the improvements. As far as we know, this is the first paper to examine the literature from a combinatorial point of view, for both KPIs and improvement options, and to make the link between KPIs and improvement options.

As indicated, simulation is extensively used to investigate ED performance and test improvements because it has multiple advantages over other OR/OM techniques (e.g. [20, 57]). Gul and Guneri [54], Paul et al. [104] and Salmon et al. [114] published a review on ED simulation. Gul and Guneri [54] classify the literature based on the conditions under which the ED is investigated, namely normal or disaster conditions. Paul et al. [104] discuss the motivation and goals, modelling techniques, patient classification and patient flow, data collection methods and study findings of all papers included in their review. Salmon et al. [114] categorise papers according to purpose, application area, method, scope and sponsor. The focus of the present review is different, and since research on ED simulation is growing, additional recently published articles are included.

This paper is structured as follows. Section 2 gives an overview of the literature search strategy. The KPIs used to investigate ED performance are specified in Section 3. Section 4 describes improvement options suggested in the reviewed literature in order to improve ED performance. In Section 5, the relation between

KPIs and improvement options is discussed. Finally, Section 6 provides a conclusion and opportunities for future research.

## 2. Literature search strategy

The goal of this paper is to provide a structured overview of the scientific literature on ED simulation. The amount of literature on this topic is large, as a result of the international recognition of the crowding problem in EDs. Because the interest in this topic comes from both the operations research and healthcare community, the large amount of literature is scattered across several research domains. To find relevant literature within the scope of this review, a three-step computerised search strategy was employed.

The first step consisted of a broad search in electronic bibliographic databases like EBSCOhost, Google Scholar and Web of Science. In order to avoid overlooking relevant literature, the search terms used in this step remained general. Articles with 'emergency', 'emergency department', 'healthcare', 'operations research', 'crowding', 'patient flow', 'hospital' or 'acute care' in the title, abstract or as main topic were identified. In a second phase, more specific search terms were used. Additional keywords include 'simulation', 'simulation optimis(z)ation', 'analysis', 'optimis(z)ation', 'performance', 'improvement', 'input', 'throughput', 'output', 'waiting', 'boarding', 'key performance indicators', etc. All articles were screened on date of publication, journal and relevancy. Only articles published since 2000 in English-language journals with an Impact Factor (based on the Impact Factors of 2017 by Thomson Reuters) are considered. The articles originate from both operations research and more medically focused journals. In addition to journal articles, conference papers, especially from the Winter Simulation Conference, are included because ED simulation is a common subject at conferences. Relevancy implies that articles within the search space are only retrieved if the main goal is the application of simulation techniques to analyse and/or optimise ED performance, and this becomes apparent from screening the title, keywords and abstract. Publications in which the complete hospital or several inpatient units are simulated, are included if the ED is part of the simulation model and the effect of changes in other departments on ED performance is discussed. Additionally, the focus is on the operation of an ED under normal conditions. Articles analysing and/or optimising ED performance in case of unforeseen events and disasters are not included. In the third step of the literature search, the ancestry approach is applied. This implies that the references of retrieved articles are pursued to gather additional papers. The selection criteria remain the same as in the first two steps.

This search strategy resulted in a final set of 107 representative publications, which are classified in this literature review. All 107 articles discuss one or more KPIs, while 100 of them also investigate opportunities for improvement. The other 7 articles only analyse the current performance of the ED. In Figure 1, the papers included in this literature review are classified based on the year of publication. The graph confirms the increasing interest in ED simulation studies. The number of yearly ED simulation publications stagnated the last years, but has witnessed a sharp increase throughout the years.

## 3. Classification based on KPIs

When applying OR/OM techniques to analyse and optimise the operations of an ED, defining the key performance indicators (KPIs) is a first, essential, step [51]. Researchers have to decide upon the measures used to evaluate ED performance and improvement options. Welch et al. [136] and Wiler et al. [142] both developed a framework to classify the existing KPIs. Welch et al. [136] classify ED performance measures into time measures, proportion measures and census, and utilisation definitions and -markers. The framework of Wiler et al. [142] shows some overlap with the framework of Welch et al. [136]. They distinguish four categories of KPIs: operating characteristics, time metrics, proportion metrics and utilisation measures. Furthermore, both frameworks standardise key definitions related to ED operations. This standardisation improves the comparability and understandability of operations research in EDs.

The classification in this review is based on the frameworks of Welch et al. [136] and Wiler et al. [142]. Adjustments are made to these frameworks based on the KPIs found in the reviewed literature. The category of budget-related measures is added and productivity measures are included in the utilisation

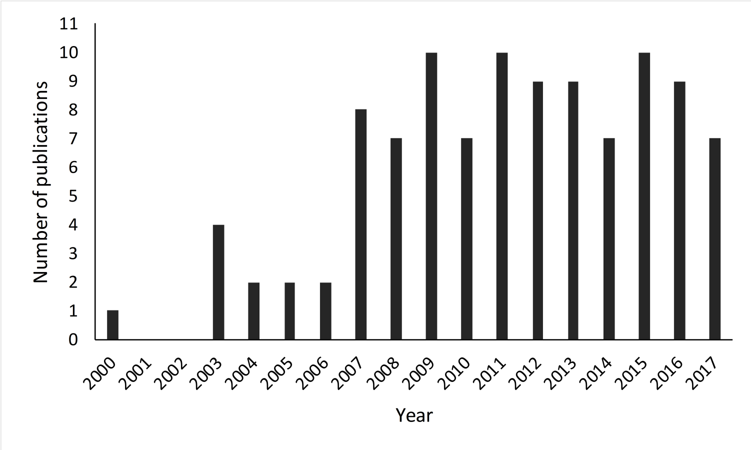



Figure 1: Number of ED simulation publications per year

category. Furthermore, the KPIs are divided into ED KPIs and inpatient unit (IU) KPIs. ED KPIs are direct indicators of ED performance. Since EDs and IUs are interconnected [49], studies analysing the ED sometimes take the IUs into account. Especially when analysing and improving the output part of an ED, IU KPIs are highly relevant to examine the link between the different departments of a hospital. Also, several studies (e.g. [58, 83, 118, 131]) propose changes in the IUs as solution for the crowding problem, since improvements in the IUs may impact ED performance.

Both ED and IU KPIs are subdivided into qualitative and quantitative measures. The large number of quantitative KPIs found in the literature is subdivided into four categories: time-related, proportions, utilisation and productivity, and budget-related measures. Each category of the classification scheme contains several KPIs and only the most frequently used are included separately in the classification. The others are grouped in a residual category, named 'other'. The next subsections give an overview of the categories and the included KPIs with a definition, (dis)advantages and references to studies applying these KPIs. Furthermore, the number of KPIs simultaneously taken into account when analysing and optimising ED performance is discussed. Some researchers only look at a single KPI to assess performance, while others analyse several KPIs. Four types of KPI-combinations are identified in the literature: a single KPI, multiple KPIs analysed separately, a single KPI in the objective function of an optimisation problem with additional KPIs included in the constraints, and multi-objective studies trying to optimise ED performance based on a set of KPIs under consideration. The classification scheme and an overview of the KPIs used in each paper, can be found in Tables A.1 to A.4 of Appendix A. The reviewed papers are assigned to one of the four tables based the type of KPI-combination used.

### *3.1. ED KPIs*

#### *3.1.1. Qualitative KPIs*

Qualitative measures are important indicators of ED performance, especially because they deal with patient experience and providing good care for patients is the main goal of an ED. The category of qualitative measures consists of patient satisfaction and patient safety. Both are negatively affected by crowding, making them suitable to measure the extent of the crowding problem [1]. In operations research, their use is limited because of the difficulties in assessing qualitative KPIs by objective scores. Pines et al. [108] make use of a survey to measure patient satisfaction. Adan et al. [3] and Ismail et al. [65] approximate patient satisfaction as a weighted combination of single indicators, such as waiting time, cancelled elective operations, layout efficiency, patient throughput and capacity excess. This measure is less subjective, but the determination of factors influencing satisfaction, and their weights, stays intuitive. Patient safety is one of the most important objectives of an ED, making it an interesting KPI. In existing literature, patient safety is approximated by

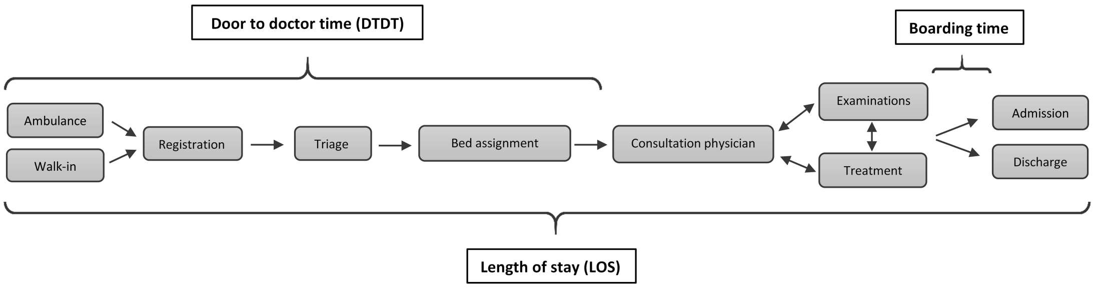



Figure 2: General patient flow with time-related KPIs

ED waiting times and readmission risk [10, 36, 62, 63, 86]. But as with patient satisfaction, there exists no measure that covers the entire concept of patient safety without any bias.

### *3.1.2. Time-related KPIs*

Time-related KPIs are commonly used, resulting in nearly all reviewed papers including at least one time-related measure of ED performance. One of the reasons is that the most tangible negative effects of ED crowding are time-related. Extended waiting times are widely recognised as a negative effect of ED crowding by patients, caregivers and researchers. Furthermore, time is easy to measure and frequently registered in electronic health records, making time-related KPIs easily accessible, unbiased and objective. Several governments impose maximum limits on time-related KPIs. Examples are the Canadian government introducing a maximal door-to-doctor time and length of stay based on triage levels, a maximal total waiting time of 6 hours in Ireland, and the UK policy makers setting a length of stay limit of 4 hours [37, 44, 52, 55, 56, 65, 92, 99]. These measures confirm the importance and wide application of time-related KPIs. Figure 2 displays the general patient flow through an ED with an indication of the most relevant time-related KPIs.

*Length of stay*

Length of stay (LOS) is the most frequently used KPI. Of the reviewed research articles, 65% use LOS as a measure for ED performance. Length of stay is defined as the time between arrival and departure in the ED (see Figure 2). It is the sum of all waiting and process times of a patient in the ED, making it an indicator of total system performance. Arrivals are either by ambulance or walk-in, a departure may occur in the form of an admission to an inpatient unit or a discharge home. Often a distinction is made between the LOS of admitted and discharged patients when analysing an ED [142]. The reason is that ED LOS is only a small part of the total LOS of admitted patients, as they stay in the hospital for several days. This makes ED LOS a less important KPI for admitted patients. A disadvantage of LOS as KPI to evaluate ED performance is that the specific problem area in the ED cannot be identified [51]. Furthermore, LOS is impacted by factors outside the control of the ED, such as internal units and demographic factors [49, 51]. A final consideration that has to be made, is that LOS and the different components of LOS differ between patient types (e.g. triage codes, admission or discharge, etc.), so overall LOS may be misleading [26, 112]. LOS is a relevant KPI to evaluate ED performance, but care is recommended when interpreting this metric.

*Door-to-doctor time*

A second prevalent time-related KPI is door-to-doctor time (DTDT). Door-to-doctor time is the time interval between arrival in the ED and the first contact with a physician [51, 142]. It consists of the process times of registration, triage and bed assignment. In addition, the waiting times for these processes to start and the waiting time for the first consultation with a physician are included (Figure 2). Especially for critical patients, DTDT is a crucial KPI [42]. It measures the most critical period of their stay in the ED, since they need urgent care. As soon as a physician has seen the patient, a diagnosis can be made and the

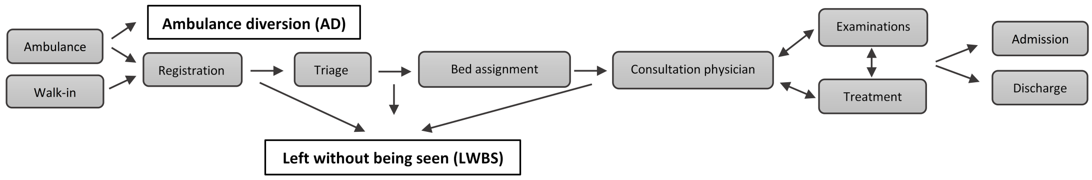



Figure 3: General patient flow with proportion KPIs

treatment can start [51, 52]. DTDT is strongly linked to patient satisfaction, especially for urgent patients. For patients with low acuity, the application of DTDT as a KPI is less useful. The reason is that these patients attach importance to the total time they spend in the ED rather than the DTDT [42]. The use of DTDT as only KPI is limited, given the low relevancy for several patient types. In 17% of the articles in this review, DTDT is used in combination with other KPIs. DTDT is frequently combined with LOS, since high urgency patients attach importance to DTDT and other patients to LOS [33, 113]. DTDT is also combined with other performance measures, such as waiting times, personnel utilisation and IU KPIs (e.g. [41, 76, 82, 83]).

*Boarding time*
Boarding time is the time between the decision made by a physician to admit a patient and the time a patient leaves the ED to an inpatient unit [137]. In Figure 2, boarding time is the waiting time between completion of the consultation-examinations-treatment cycle and the time the patient is admitted to an inpatient unit. Extended boarding times are one of the main causes of ED crowding [25, 124]. The last years, the amount of research focusing on boarding increased as a result of the general recognition of the problem. Only 7% of the papers include boarding time as a KPI, but they are all published in the last 10 years. This confirms the growing interest in boarding as a research topic within operations research for EDs. As research into boarding only recently emerged, and boarding time is only relevant to admitted patients, boarding time is mostly considered in combination with other KPIs.

*Other*
The residual category of time-related measures mostly contains waiting times, as these are often a waste of time and could be reduced [101]. Every process a patient undergoes in the ED may be preceded by some time waiting for the process to start, so every arrow in Figure 2 may induce a waiting time. About 52% of the papers include one or more waiting times as KPI. Waiting time for registration, triage, bed assignment, physician or nurse consultation, results of laboratory or radiological examinations, and discharge are all examples of KPIs used to examine ED performance. In addition to waiting times for a single process or event, total waiting time for a patient during its stay in the ED is a popular metric. Several researchers differentiate the total waiting time between triage codes (e.g. [46, 59, 95, 91]) or acuity levels (e.g. [35]). Others look at the total waiting time in the different subunits of the ED (e.g. [37, 67]). In addition to waiting times, this category also contains time intervals related to value added activities. Examples are the total value added time of an ED visit [14] and the total treatment time [35, 65]. Since multiple KPIs are included in the residual category, the presence of this KPI type is not always restricted to a single KPI per reference (e.g. [6, 134]).

*3.1.3. Proportion KPIs*

Not all aspects of ED performance can be represented in time units. Proportion KPIs describe the occurrence of ED crowding effects as a relative measure with respect to the total sample size [142]. Ambulance diversion (AD) and left without being seen (LWBS) are two well known consequences of ED crowding, both expressed in terms of proportions. Figure 3 indicates where in the general patient flow AD and LWBS occur.

*Ambulance diversion*

Ambulance diversion is an intervention to reduce the arrival rate to the ED at moments of high occupancy [50, 112]. During times of ambulance diversion, new incoming ambulances are refused and re-routed to nearby hospitals [51]. In Europe, ambulance diversion is rarely applied since most countries forbid the refusal of patients arriving at the ED. Also, ambulance diversion has negative moral consequences for the patients and implies financial losses for the hospital. However, in the US it is common practice. This makes the time a hospital is in a state of ambulance diversion a good approximation of ED crowding [51]. Ambulance diversion is expressed as a percentage of time relative to the time period under investigation [78, 107, 136] or an amount of time per time period [36, 77]. It is used in only 5% of the papers and always in combination with other KPIs. Geiderman et al. [50] indicate that the practice of ambulance diversion is related to boarding time and the occupancy of inpatient units. Apart from the relation with outflow, AD is an interesting measure to look at in combination with financial KPIs, since AD implies lost patients and therefore lost revenue.

*Left without being seen*

Left without being seen (LWBS) is defined as the percentage of patients who leave the ED before being seen by a physicianby [136, 142]. Patients may leave the ED after registration, triage or bed assignment, so before the first consultation with a physician (see Figure 3). The percentage of LWBS patients is influenced by ED occupancy and waiting times, which makes LWBS a consequence of ED crowding [27]. Patients who leave without being seen by a physician are exposed to a safety risk if they have serious health problems [50]. The relation with ED crowding and patient safety makes the use of LWBS as KPI to evaluate ED performance highly relevant. Nevertheless, the use of LWBS has some disadvantages. LWBS is influenced by external factors such as the existence of other nearby care facilities, the distribution of patients according to triage level, and demographic factors. This makes comparing EDs based on LWBS difficult. Also, investigating LWBS patients and their behaviour is hard, since ED staff does not immediately notice the departure of a patient [51]. Moreover, the number of patients who leave the ED without a consultation with a physician is a minority of the total number of patients visiting the ED. Because of the disadvantages, LWBS is barely used as the only KPI in simulation studies. Nevertheless, 12% of the reviewed papers include this KPI. Frequently, time-related measures are included in addition to LWBS (e.g. [36, 48, 94, 97, 134]). Furthermore, several studies incorporate utilisation measures (e.g. [1, 65, 101, 149]) or budget-related KPIs (e.g. [107]) in combination with LWBS when analysing ED performance.

*Other*

Ambulance diversion and left without being seen are the most common proportion measures, but others exist. Most KPIs in this category are proportions of patients that meet time-related targets. As already indicated in Section 3.1.2, the UK government imposes a LOS limit of 4 hours that should be met for 98% of the patients. As a result, the percentage of patients that satisfy this target is frequently used as a measure for ED performance [37, 44, 56, 66, 92]. Apart from this standard, Day et al. [38] and Ismail et al. [65] examine the percentage of patients with a LOS exceeding 6 hours. In addition to proportions related to LOS, a common measure is the percentage of patients for which the DTDT exceeds a predefined target. Most of the time, the target depends on the triage code of the patient and is defined by the triage scale in use [9, 10, 41, 144, 148]. A final proportion measure related to time is the probability that a patient has to wait before a specific process starts [66].

This residual category also contains proportion measures that are completely independent from time-related KPIs. Ferrin et al. [48] and Vissers et al. [131] both use the percentage of ED patients accepted for admission and the percentage of time the ED is at full capacity as KPIs. The percentage of ED patients accepted for admission is only relevant if the hospital under study may refuse to admit ED patients to IUs in case of high occupancy rates. The refused patients are sent to another, nearby hospital. Another measure is the percentage of patients initially assessed by a specific physician. This is used as a proxy for physician productivity by Wang et al. [132]. Finally, Shi et al. [118] develop a simulation model to determine the effect of placing admitted patients in empty beds on another IU than the desired one based on their diagnosis.

This option is considered after a certain threshold value for boarding time has been reached. The overflow proportion indicates the percentage of ED patients placed in a suboptimal inpatient unit.

### *3.1.4. Utilisation and productivity KPIs*

High personnel utilisation is argued to be a major consequence of ED crowding, leading to high stress levels for ED staff [18, 99]. Furthermore, resource utilisation in general is correlated with longer LOS, patient dissatisfaction and even costs [142]. Nevertheless, Abo-Hamad and Arisha [1] state that resource utilisation and productivity are not frequently enough considered as KPIs. Utilisation is defined as the ratio of active hours to total available hours of a resource. It is further divided into personnel and equipment utilisation. Utilisation measures differ from all other KPIs in that there is no clear minimisation or maximisation goal. Utilisation ratios near 100% undermine the availability to provide quick and qualitative care to all patients. On the other hand, low utilisation ratios are not interesting from a financial point of view. There exists a trade-off between service and costs. Frequently, a target value is defined and this value is case/situation dependent. Utilisation ratios exceeding this threshold may indicate bottleneck resources.

The second part of this category, productivity, is related to resource utilisation as it focuses on the number of patients completed by the available resources within a certain time period. Welch et al. [136] use the category of census measures to assess the number of patients meeting certain conditions, such as the number of patients arriving and completed in the ED, but also numbers related to patient mix and characteristics (e.g. number of patients per triage code). As the latter part are descriptive measures rather than performance indicators, the category is renamed to productivity measures and includes only KPIs linked to ED performance.

*Personnel utilisation*

Personnel utilisation refers to the percentage of time the different classes of ED staff are busy. Physicians, nurses, triage nurses, logistics personnel, administrative personnel, etc. are all personnel classes for which the utilisation can be evaluated. Nurse and physician utilisation are the utilisation KPIs most obviously affected by ED crowding. Most of the time, these are also the bottleneck resources in the ED. Consequently, the majority of papers taking personnel utilisation into account focus on these human resources. However, the bottleneck resource depends on the specific ED, so the utilisation rate of other human resources may also be relevant [120]. 28% of the reviewed studies include the utilisation of one or more personnel types to measure ED performance. Since personnel utilisation indicates the effect of ED crowding and improvement options on ED staff, and is only indirectly linked to patient experience, this KPI type is frequently combined with other measures. Time-related KPIs (e.g. [5, 14, 53, 79, 81, 139]) and proportion KPIs (e.g. [65, 101, 148, 149]) are commonly added for a more direct patient focus.

*Equipment utilisation*

Equipment in the ED, among other things, consists of beds, laboratory equipment and radiological devices. Only restricted resources are possible bottlenecks, so medication utilisation or blood draw equipment utilisation are no relevant KPIs for example. Of the reviewed papers, 13% incorporate equipment utilisation as KPI. Bed utilisation is the most prevalent KPI in this category and is sometimes split into the different types of beds present in an ED (e.g. resuscitation rooms, paediatric beds, fast track beds, etc.) (e.g. [1, 31, 43, 53, 73, 101, 103, 133]). For radiological equipment, a distinction can be made based on equipment type (e.g. CT-scans, X-rays, MRI) [22, 46, 64]. Most of the time, equipment utilisation is examined in combination with personnel utilisation.

*Patient throughput*

Patient throughput is the number of patients disposed from the ED per time unit, either by admission or discharge [4]. In case of crowding, patient throughput is an indication of the productivity of the system and an increased throughput reveals a reduction of the crowding problem. A disadvantage of throughput is the dependency on the number of arrivals, demographic factors and the size of the ED, making this measure not suitable to compare between EDs. Several researchers combine patient throughput with other KPIs when evaluating ED performance. Combinations of patient throughput with utilisation measures (e.g. [115, 53, 67, 103]), as well as proportion KPIs (e.g. [9, 90, 101]) and time-related measures (e.g. [4, 29, 43, 53, 105]) are all apparent in existing literature. In total, 15% of the reviewed papers discuss patient throughput.

*Other*

The 'other' subcategory contains rarely used utilisation and productivity measures. A first measure, layout efficiency, is approximated by the distance nurses, physicians, patients and equipment have to travel in the ED during a shift. Travel time is 'lost' time and reduces productivity of ED resources [1, 65, 75]. A second metric in this category is ED crowding. The degree of ED crowding is measured by the NEDOCS-score (i.e. National Emergency Department Crowding Scale) or a self-defined measure [13, 76, 64, 88, 138]. Nevertheless, it is difficult to capture every aspect of ED crowding in one measure, explaining their limited use. A third measure, which is related to ED crowding, is the average number of available beds in the ED [135, 148]. Both ED crowding and a low average number of available beds cause high utilisation rates and a lower productivity. A fourth KPI, patient census, is defined as the number of patients simultaneously present in the ED on a certain moment [78, 81, 94, 95]. A fifth KPI is the queue length of a specific process or the total number of patients waiting in a queue throughout the entire ED [78, 84, 86, 115, 118, 132, 143]. As these two measures are census measures, and a high patient census or queue length can reduce productivity, they both fit in this category. Finally, Rachuba et al. [109] examine the effect of a radiographer-led discharge policy on the number of discharges made by the radiology department and on the number of clinical assessments by ED physicians.

### 3.1.5. Budget-related KPIs

The use of budget-related KPIs is rather scarce in OR studies concerning ED operations [54]. This is reflected by the fact that the classifications and operations dictionaries of Welch et al. [136, 137] and Wiler et al. [142] contain no measures related to costs or revenue. However, ED crowding has an important financial impact, as already indicated in Section 3.1.3. ED crowding leads to ambulance diversion, left without being seen patients and cancellations of elective patients. AD and LWBS result in less patients treated and charged by the hospital. Elective cancellations are replaced by ED patients, so the number of treated patients stays equal, but elective patients are more profitable [107]. Furthermore, financial KPIs are interesting for hospitals when analysing and comparing improvement scenarios. Especially when the goal is to implement improvement scenarios, the financial impact is an essential decision factor for hospital management [47, 46, 107]. A prerequisite to be able to implement budget-related KPIs is the ability to express the effects of ED crowding in financial terms.

Budget-related KPIs are subdivided into cost-related and revenue-related measures. In total, 13% of the papers in this review include a budget-related KPI. The cost of improvement scenarios is frequently used as KPI in simulation-optimisation studies. Simulation-optimisation is the process of finding the best values of some parameters for a system, where the performance of the system is evaluated based on the output of a simulation model [4]. Simulation-optimisation combines analysis and optimisation, and is an alternative for what-if scenarios. A simulation-optimisation approach requires the formulation of an objective and constraints. Ahmed and Alkhamis [4], Centeno et al. [30], Chen and Wang [32] and Guo et al. [59] include costs in the objective function, while Cabrera et al. [23], Ghanes et al. [52], Keshtkar et al. [73] and Zeinali et al. [147] impose a limit on the available budget in the constraints in order to take costs into account when optimising ED performance. Three papers examine revenue instead of costs [16, 86, 107]. Beck et al. [16] and Lee et al. [87] use simulation-optimisation to maximise profit.

## 3.2. IU KPIs

Because IU KPIs are indirectly related to ED performance, they are included in the framework. The category is subdivided in the same way as ED KPIs, but they are not discussed in great detail, as the primary focus of this literature review is on measuring and improving ED performance. In total, 11% of the reviewed papers include at least one IU KPI. The only qualitative IU KPI present in the reviewed publications is patient satisfaction [3]. The quantitative measures consist of time-related, proportions, and

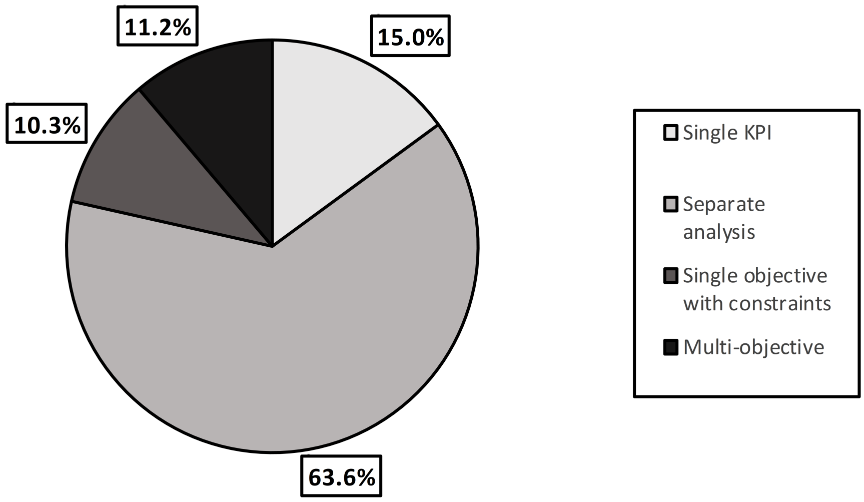



Figure 4: Proportional distribution of literature based on type of KPI-combination

utilisation and productivity measures. Budget-related performance of IUs is not discussed in the reviewed simulation studies.

The time-related KPIs are subdivided in two groups: LOS and 'other'. The length of stay in an inpatient unit, which is the time between admission to the IU and discharge, is considered by Gunal and Pidd [58] and Wong et al. [143]. DTDT and boarding time are not relevant in an IU. The 'other' category of time-related IU KPIs includes the waiting time for elective patients before admission to an IU [58, 130], and the total time ED patients and outpatients spend in an acute medical unit before an IU bed is available [116].

In the proportions category, the percentage elective cancellations is the most used KPI. This indicates how many planned admissions have to be cancelled as a result of high hospital occupancy in combination with a high number of ED admissions [58, 83, 107, 131]. The first proportion KPI in the residual category is the percentage of elective patients with a waiting time for admission that exceeds 18 weeks, which is a target value of the hospital under study [58]. The second KPI is the total percentage of patients (including ED patients) refused hospital admission [116]. AD and LWBS are only applicable in an ED.

Utilisation and productivity KPIs are the most popular category of IU KPIs, with 82% of the papers that consider IU KPIs belonging to this category. Hospital occupancy, also called bed utilisation, indicates the percentage of IU beds that are occupied [17, 46, 76, 77, 83, 116, 118]. The residual category contains hospital inefficiency [3], 08:00 hour patient census [143], the number of weekly discharges from IUs [143], total number of elective patients treated annually [58] and the number of elective patients not admitted to the preferred IU [58]. The use of hospital occupancy as single IU KPI is common, but other IU KPIs are mostly used in combination. As this is a literature review of simulation studies analysing and optimising ED operations, most papers with one or more IU KPIs also include ED KPIs.

### *3.3. Combinations of KPIs*

In the previous sections, the KPIs used in existing simulation literature on ED performance are described. This section focuses on the number of KPIs simultaneously taken into account when analysing and optimising ED performance. From Tables A.1-A.4 and the discussion above, it is clear that most researchers take more than one KPI into account. Figure 4 visualises the proportional distribution of the reviewed literature based on the type of KPI-combination used: a single KPI, multiple KPIs analysed separately, a single KPI in the objective function of an optimisation problem with additional KPIs included in the constraints, and multi-objective studies trying to optimise ED performance based on a set of KPIs under consideration.

Table A.1 gives an overview of the ED simulation studies that focus on a single KPI. As is clear from Figure 4, only 15% of the reviewed literature belongs to this category. The majority of studies in this category has LOS as only KPI (56%). Only 3 papers focus on a non time-related KPI. As one KPI provides restricted information on ED performance, the use of multiple KPIs is recommended.

The second type of KPI-combination contains research articles examining multiple KPIs, but separately. An overview of these papers can be found in Table A.2. This is by far the largest group, with 63.6% of the articles being part of this category. Multiple KPIs can be chosen in a way that they complement each other [51]. ED performance and improvement scenarios are then evaluated by use of multiple metrics to get a more complete view. The disadvantage of this approach is that finding an optimal solution based on all KPIs is difficult, if not impossible. The result is that these studies describe ED performance and the effect of improvements on multiple aspects, but deciding on the best improvement is hard, especially when conflicting KPIs are included. All but 3 papers include one or more time-related measures in their set of KPIs and 21% of the papers in this category include only time-related KPIs. The others look at combinations of KPIs across different categories. The use of qualitative, budget-related and IU KPIs is rather scarce.

From the findings of Tables A.1 and A.2, it is clear that time-related KPIs play an important role when analysing and/or optimising ED performance. Either these KPIs are best suited to approximate ED performance, or they are easily assessable. As ED crowding is, among other things, recognised by high waiting and throughput times [19, 99], and timestamps of ED activities are frequently registered in electronic health records, both reasons are credible.

A third combination type, encountered in 10.3% of the reviewed literature, optimises ED performance with respect to a single KPI while dealing with additional KPIs in the constraints. This way, an optimal decision can be made based on one KPI without completely neglecting other important performance measures. A minimum, maximum or both are imposed on the additional KPIs, making sure these (frequently conflicting) KPIs stay within acceptable limits. The papers applying this approach are summarised in Table A.3. The approach is superior to the first two, but still not optimal. By deciding beforehand on the limits of several KPIs, some solutions are automatically considered infeasible while these may be superior to the current decision. This method is mainly applied in simulation-optimisation studies. Most of them try to minimise LOS with respect to a maximal DTDT for critical patients, budget restrictions and capacity or utilisation limits.

Finally, the fourth and most desirable approach, is a multi-objective approach. This approach has several advantages over the other approaches. It involves the simultaneous optimisation of multiple KPIs, so a comprehensive set of KPIs to cover all relevant aspects of ED performance can be considered. This may be interesting as many ED KPIs are conflicting in nature. Multi-objective problems are characterised by the fact that no unique optimal solution exists. Instead, a Pareto frontier is composed consisting of all the solutions that perform equally (and optimal) based on the set of KPIs under consideration. A solution is on the Pareto frontier when there exists no other solution which performs at least as good on all KPIs and better for at least a single KPI. A trade-off has to be made between the importance of the different KPIs when selecting a final best solution, based on the preferences of the decision maker [96]. Methods to deal with multi-objective decision making (i.e. to construct the Pareto front) include the scalarization or weighted-sum method, $\epsilon$-constraint method, goal programming, data envelopment analysis and multi-objective combinatorial optimisation by metaheuristics [24]. While a multi-objective approach seems the most promising method for analysing and especially optimising ED performance, only 11.2% of the reviewed literature takes on this approach. In addition, the Pareto front is constructed in only three papers [3, 32, 47]. The number of KPIs under consideration when creating a Pareto front is often limited to two or three. All other multi-objective papers determine the importance of the different KPIs a priori and try to find the single optimal solution based on the predefined preferences.

In Table A.4, an overview of the multi-objective literature is given. The literature is classified based on the multi-objective method used. The scalarization or weighted-sum method involves the construction of a single objective function as the weighted sum of the different objectives. A weighted objective function implies the assignment of weights to the different KPIs. Based on these weights, the weighted sum of all KPIs is calculated and an overall score is given to the improvement scenarios. By taking different weight combinations into account, a representative part of the Pareto front can be constructed. However, all papers that apply the weighted-sum method use only one weight combination and as a result, only one solution to the problem is found. The weights are defined by the importance of, or preference for, certain KPIs, but this can differ between patient types (e.g. DTDT of high acuity patients is assigned a higher weight than DTDT of low acuity patients) [33, 113]. The bundle of KPIs included in the objective function can be broad, containing time-related, proportions, utilisation and productivity, and budget-related KPIs. This method is applied by Abo-Hamad and Arisha [1], Chonde et al. [33], Eskandari et al. [46] and Saghafian et al. [113]. The second multi-objective method present in ED simulation studies is goal programming. In goal programming, goals are set for the different objectives (i.e. KPIs) and the deviation from these goals is minimised [24, 96]. This approach is used by Adan et al. [3] and Jerbi and Kamoun [67]. Data envelopment analysis is used by Al-Refaie et al. [5] to identify the best improvement scenario. Data envelopment analysis is a multi-objective technique which makes use of a single objective, relative efficiency, to evaluate the efficiency of a group of organizational units (or decision-making units) that use multiple inputs to produce multiple outputs [139]. A fourth multi-objective method present in the reviewed literature is multi-objective combinatorial optimisation by metaheuristics. Chen and Wang [32] and Feng et al. [47] both use a multi-objective evolutionary (genetic) algorithm to solve an optimisation problem with multiple conflicting objectives. Finally, Crawford et al. [36] and Kolker [78] graphically analyse ED performance, in which different KPIs are displayed against each other to see the relationship, and possible trade-off, between them. This method does not optimise performance, but rather analyses the trade-off between different objectives.

*3.4. Research opportunities*

As is clear from the discussion above, opportunities exist for future research on ED simulation with respect to the KPIs used to measure ED performance. A first finding is the extensive use of time-related KPIs in comparision with other categories. Time-related measures are patient-centred, but personnel and hospital interests should also be emphasised in the KPIs. The three least investigated categories are budget-related, qualitative and IU KPIs. Budget-related KPIs seem important when evaluating improvement options, especially when considering an implementation, but are only used in 13% of the simulation studies. Qualitative ED KPIs are also infrequently used, but as these are difficult to measure and related to quantitative KPIs (e.g. high waiting times lead to unsatisfied patients and safety risks), this is justifiable. The scarcity of IU KPIs is not surprising, given the focus on ED performance. If we look at the individual KPIs in the classification, in addition to all qualitative, budget-related and IU KPIs, AD and boarding time are used in less than 10% of the studies. This is reasonable for AD, given the controversy about its use [50]. For boarding time, this finding is remarkable, since boarding is cited as one of the main causes of ED crowding.

Concerning combinations of KPIs, opportunities exist in the multi-objective field. The multi-objective approach is applied in only 11.2% of the reviewed articles. As a result, a lot of combinations of KPIs have not yet been considered in a multi-objective context. For the investigated sets of KPIs, the findings still need confirmation as they are, for most combinations, based on a single case study. In addition to the opportunities for combining KPIs, methodological challenges exist in the area of multi-objective ED simulation. Only three papers construct a Pareto front in order to solve the multi-objective problem, the most widely accepted approach in multi-objective research [3, 32, 47]. Also, some other promising methods to apply multi-objective research can be identified in addition to the methods already present in the reviewed articles. An example is the $\epsilon$-constraint method. In this method, one objective is maximised or minimised in the objective function, and the other objectives are included in the constraints with a target value. This target value can be varied in order to obtain different (optimal) solutions of the Pareto front [24, 96]. The $\epsilon$-constraint method has proven to be effective to find the Pareto optimal set of personnel planning solutions in order to minimise both patient waiting times and personnel costs (without using simulation) [126]. A second method that has been applied in an ED context (but not in simulation research) in order to optimise resource management according to six criteria, both quantitative and qualitative, is the Promethee II outranking method [7]. Also, as multiple variations on the different multi-objective methods exist, investigating other approaches of methods that are already applied (see Table A.4) can be interesting. For example, Chen and Wang [32] and Feng et al. [47] both use evolutionary algorithms as metaheuristics in the multi-objective combinatorial optimisation by metaheuristics method. Caramia and Dell' Olmo [24] mention simulated-annealing and tabu search as other potential metaheuristics that can be used to cope with multiple objectives. An overview of the mentioned multi-objective decision making methods and several other methods, with some advantages and disadvantages of each method, can be found in Caramia and Dell' Olmo [24], Miettinen [96] and Velasquez and Hester [129].

A final opportunity lies in the application of multi-objective simulation-optimisation. Simulation-optimisation is an interesting OR technique to optimise ED operations, but most simulation-optimisation studies optimise a single KPI with respect to several constraints. The studies of Chen and Wang [32] and Feng et al. [47] are the only ones applying a multi-objective approach in combination with simulation-optimisation. As both multi-objective and simulation-optimisation are valuable techniques to analyse and optimise ED operations, this is an interesting topic for future research.

## 4. Classification based on improvement options

The first step in analysing ED performance is deciding upon the relevant KPIs. Based on the selected KPIs, problem areas within an ED are identified. When focusing on both analysing and optimising ED performance, a second step is to determine the type(s) of improvement(s) considered in the optimisation phase. As patient flow is frequently divided into input, throughput and output, the improvement options are classified according to the appropriate stage within the patient flow.

The input stage contains all patient care processes that occur from the time of arrival in the ED until an ED healthcare provider formally assumes responsibility for the evaluation and treatment of the patient [140]. This only comprises the arrival process into the ED [11, 54, 112]. The throughput stage of patient flow consists of registration, triage, bed assignment, clinical assessment, treatment and diagnostic testing. All these processes are completely under control of the ED, while the input and output stages may be influenced by external factors [54]. The final stage of patient flow through the ED, output, covers the disposition process. A patient can be discharged or admitted to an inpatient unit [27]. Figure 5 gives a graphical view of the consecutive steps of patient flow through the ED. Arrivals are either by ambulance or walk-in. The throughput stage starts at registration. The double arrows in the figure indicate cyclical processes. After consultation with a physician, a patient may undergo examinations or treatments, and both processes can be executed several times and in any order. If a patient is medically finished, the output stage is entered, in which a patient is disposed from the ED.

Improvements in the throughput stage receive most attention in existing research, while the input and output stage are less investigated. However, these latter stages are mostly indicated as the problem areas in an ED [27]. This section gives an overview of the improvement options provided and tested in the reviewed literature. The focus is on improvements with an impact on ED operations and, consequently, patient flow through the ED. External improvements only impacting patient safety or patient flow outside the ED (e.g. ambulance location) are not included. In addition to an overview of the improvement options in each stage of the patient flow, a discussion of the combinations of improvements that are investigated is provided. Three types of combinations are identified in the reviewed literature: a single improvement, the separate analysis of multiple improvements and the combined analysis of multiple improvements. In Tables B.1 to B.3 of Appendix B, the reviewed papers are classified according to the type(s) of throughput and output improvement(s) introduced. The papers are assigned to one of the tables based on the way in which improvement options are combined. Input improvements are not included in the tables for the reasons discussed in Section 4.1.

### 4.1. Input improvements

The input part only comprises the arrival process into the ED. This has a direct impact on ED crowding, but modifications are difficult to accomplish because of several reasons. First of all, the arrival process is determined by the demand for ED services, which depends on various factors outside the control of the ED. This leads to large fluctuations in the number and acuity level of patients visiting the ED. Secondly, EDs are confronted with an increase in the demand for emergency services. Besides, the demand for ED services is highly unpredictable [18, 93]. Lastly, in many countries legislation states that EDs are obliged to provide

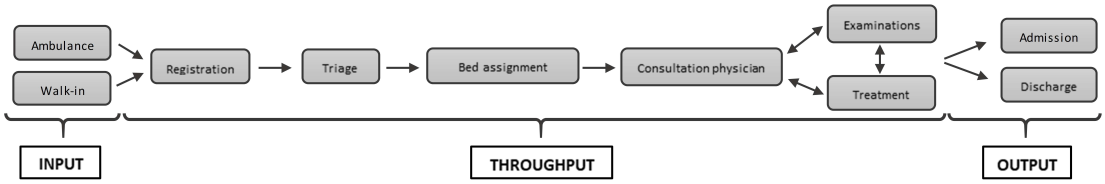



Figure 5: General patient flow through an ED

care to every arriving patient. This makes it impossible to refuse patients when the ED is in a state of crowding [27].

Despite the difficulties in altering the arrival process, admission control (i.e. the control of patient inflow to the ED) is repeatedly proposed as a solution for ED crowding. Admission control can be attained in several ways, with ambulance diversion (AD) being the predominant method, especially in the US. Ambulance diversion is the practice of re-routing ambulances to other, nearby hospitals, if the ED is crowded [8, 40, 50]. The idea behind AD is to reduce ED crowding by restricting arrivals for a period of time [106]. Some researchers mention positive effects of AD on ED crowding (e.g. [84, 88]). Nevertheless, there are several disadvantages associated with AD. Deo and Gurvich [40] and Vile et al. [130] mention a limited effect of AD on waiting times and LOS. In addition to the questionable benefits, patient safety of diverted patients may be jeopardised. Other adverse effects of AD pointed out in previous research are a delay in patient transport and treatment, lower ambulance availability and poorer health outcomes [8, 50]. Sometimes it is even linked to higher mortality rates [40, 106]. Lastly, AD implies a negative financial effect for a hospital, since patients who otherwise generated revenue are diverted to other hospitals [106]. Besides the questionable benefits for the patient and hospital, there are also ethical issues related to AD [50]. The disadvantages in combination with the fact that an ED is supposed to provide care to any patient, results in several countries prohibiting AD.

A second input solution to the crowding problem, is discussed by Borgman et al. [21]. Their research focuses on the effect of integrating a general practitioner post within the ED. The trend toward using the ED for non-emergency care is one of the factors contributing to ED crowding. Those patients are mostly self-referring patients exploiting the accessibility of the ED. The general practitioner post allows to distinguish patients based on their complaints, and only patients with urgent needs are admitted to the ED. The patients inappropriately presenting themselves at the ED are treated by the general practitioner, restricting the inflow to the ED [21]. Lee et al. [86] and Vile et al. [130] introduce the concept of an alternative care facility for non-urgent or walk-in patients, which is comparable with a general practitioner post.

Whereas both solutions may reduce ED crowding, they will not be discussed in more detail. First of all, in several countries regulation impedes EDs to deny access to patients, making AD impossible. Secondly, the institution of a general practitioner post is a promising concept, but little research has been done. A possible explanation is the fact that implementing a general practitioner post in every ED is complex and costly.

### *4.2. Throughput improvements*

Improvements in the throughput phase are most popular among researchers. The throughput part of patient flow is completely under control of the ED, making this the most attractive and least complicated part to intervene.

*Triage interventions*

Triage is one of the first processes a patient undergoes after entering the ED. In most EDs, patients are seen by a nurse, after which a severity index, mostly based on a 3- or 5-level scale, is assigned. This index defines the priority of the patient in the next stages of the throughput phase [62]. Several triage classification systems exist, like the Manchester Triage Scale and the Emergency Severity Index. 11% of the papers investigate the effect of reorganising the triage process on patient flow through the ED. A first improvement option is altering the classification rules of triage, including more factors than only urgency. One possibility is to take the expected disposition type into account [113]. Another option is a classification based on urgency and complexity. Complexity is defined as the expected number of interactions a patient will undergo (i.e. consultations and examinations) [62]. Ashour and Okudan Kremer [9, 10] take complaints, demographic factors, pain level and vital signs into account. Their triage classification consists of more levels to overcome the issue of defining priorities within an ESI-triage level. A second triage intervention is the introduction of physician triage or team triage. Oredsson et al. [102] define team triage as the execution of the triage process by a team that includes a physician in addition to a triage nurse. An advantage of this approach is that diagnostic tests can be ordered at triage, which is also investigated as separate improvement option (without a physician at triage) [21, 60, 90, 111, 145]. Day et al. [38] incorporate a fast track into triage, which is comparable to team triage and makes the treatment and immediate discharge of low-acuity patients from within triage possible.

*Patient streaming*

Patient streaming is the process of dividing patients in different streams according to some predefined patient characteristics. The allocation of patients to streams is done based on judgement at triage. Patient streaming is frequently included in the category of triage interventions, as an immediate connection with triage exists [27, 102]. However, triage only impacts priorities, while patient streaming impacts the physical layout, processes and resource allocation within the ED. Patient streams have their own dedicated resources and rules on patient flow. For these reasons, patient streaming is included as a separate improvement option for ED crowding.

The concept of patient streaming can be approached in two different ways: physical streaming or virtual streaming [113]. Physical streaming physically splits the ED in different areas for the different streams, and divides all resources between the streams [113]. The process of streaming low acuity patients to another area within the ED is also known as fast track. Physical streaming is a generally accepted solution and implemented frequently in EDs to reduce crowding by handling low acuity patients faster, but the specific way in which it is implemented may differ (e.g. opening hours, physical layout, streaming criteria,...) [15, 33, 37, 44, 48, 69, 71, 80, 81, 92, 94, 105, 115, 113, 135]. Another type of physical streaming is introduced by Vile et al. [130]. They stream ambulances and GP referrals to areas outside the ED (e.g. directly to the appropriate IU), so they do not pass through the complete ED process. An argument against physical streaming is the strict separation of resources between streams.

Virtual streaming only logically separates resources between the streams and in case of capacity problems, resources can be shared. Chonde et al. [33], Hopp et al. [62] and Saghafian et al. [113] make a distinction between low- and high acuity patients. Connelly [35] streams patients to physicians and nurses in a way that the ratio of low to high acuity patients is the same for every physician and nurse in the ED. In addition to the introduction of patient streaming, streaming criteria can be changed in order to find the most effective streaming rules [62, 71, 69, 105].

*Staffing and scheduling*

In case of ED crowding, increasing resource capacity is a straightforward solution, as resource shortages are a major contributor to waiting times. Among the resources used in an ED, personnel is often the most restricting resource [112]. The staffing and scheduling category refers to improvement scenarios concerning personnel capacity and personnel schedules. This type of improvement is frequently analysed, confirmed by 58% of the reviewed literature suggesting staffing and scheduling changes as improvement option. Especially adjustments to the staffing capacity are prominent. In an ED, a large diversity of functions exist, ranging from administrators and logistic personnel to nurses and physicians. For a few functions, multiple subcategories exist, like physician types based on specialism and experience level [23]. As hiring personnel is costly, it is important that the focus is on increasing the capacity of the bottleneck function [120, 133]. The bottleneck function depends on the specific ED, but often nurses and physicians are the critical resources

[82, 79].

In addition to capacity changes, staffing schedules may be improved to alleviate ED crowding. Staffing schedules deal with the allocation of resources to shift times and zones in the ED. The adaptation of shift times and assignment of resources to these shifts in order to better reflect patient demand, is a first improvement option in this category. The adjustment of start times, durations, numbers of shifts, shift types and the number of resources per shift are all investigated in the reviewed articles [26, 34, 43, 45, 53, 66, 67, 82, 101, 120, 146, 148]. A second factor related to staff schedules that may be adjusted is the allocation of staff to the different zones or patient types in the ED [5, 32, 110, 117, 133, 149]. The dynamic reallocation of personnel during a shift based on occupancy of the different zones is investigated by Ismail et al. [65] and Sinreich et al. [121]. Other improvement options are employing more experienced doctors [55], training of personnel [65, 75] and multitasking [55].

*Equipment capacity*

A fourth category of improvement options in the throughput phase is altering the equipment capacity. This is considered in 30% of the reviewed papers as a way to improve ED performance. A first equipment type are ED beds. Both the addition of ED beds (e.g. [41, 73, 147]) and switching beds between zones (e.g. [1, 26, 101]) are examined as improvement option. A second equipment type analysed in improvement scenarios is radiological and laboratory equipment. For these equipment types, the capacity (e.g. [6, 22, 34]) and the impact of using a shared or dedicated radiological/laboratory department (e.g. [32, 145]) are considered. Interestingly, only 3 papers investigate equipment capacity without simultaneously looking at staffing changes. This may be explained by the fact that adding equipment is only beneficial if this equipment can be staffed.

*Other*

The final category of throughput improvements is a rest category, containing mostly process and policy changes. Process changes mainly deal with reducing service times. Several researchers reduce radiological and/or laboratory turnaround times to examine their effect on ED performance [34, 48, 55, 64, 86, 98, 97, 103, 134]. Furthermore, the operational time of other processes (e.g. triage, nurse and doctor consultations, disposition) [14, 29, 135, 133] and waiting times (e.g. by imposing the rule that a patient has to be seen by a physician within 30 minutes after arrival) can be reduced [128, 95, 133]. Other process changes include a change of the mean time a patient spends in the ED [76], a modification of the percentage of patients undergoing specific processes in the ED (e.g. examinations, admission) [90, 128, 144], the integration of triage and registration [86, 133], the introduction of bedside triage and/or registration [16, 97, 115], the adjustment of opening hours of specific areas in the ED [15, 69, 91, 95, 148] and layout improvements [75, 148]. An important note is that most of the process changes cannot be implemented in reality. These improvement options serve as guidance to practitioners and other researchers by indicating which processes have the possibility to improve ED performance if they are executed more efficiently.

Policy changes deal with rules in the ED. One policy change is the introduction of a zero-tolerance blocking policy, involving that patients admitted to the IU may not board in the ED. This results in patients being transported to other areas of the hospital, where they are placed in waiting rooms or hallways while awaiting their admission to an IU [1, 79]. Another improvement option is the adjustment of task [29] or patient [46, 117] priorities. Other suggestions present in the reviewed literature are reallocating tasks between staff, changing the mix of physicians present in the ED, using students for several tasks, separating walk-in patients from ambulance patients, eliminating the batching of patients for several processes, changing the allocation of patients to the different zones in the ED, introducing a payment desk at the front-end of the ED, executing examinations in advance of a physician consultation and radiographer-led discharges [21, 86, 90, 109, 119].

### *4.3. Output improvements*

26% of the reviewed literature investigates one or more output improvements. This is far less than the 85% of papers including at least one throughput improvement. Nevertheless, an obstruction in the output process is one of the major causes of ED crowding [27]. Output improvements are subdivided in three categories: ED solutions, IU solutions and collaborative solutions.

*ED solutions*
Eliminating the bottleneck in the output process solely based on ED improvements is difficult. As the IU capacity remains constrained, patient flow to the IUs cannot be accelerated. However, several solution methods overcome this problem and effectively reduce ED crowding, but the practical and financial consequences of these improvements have to be taken into account. The improvements in this category mostly require additional space, equipment and/or personnel, which is costly and only possible if the ED can be expanded or reorganised. Kolb et al. [77] define patient buffer concepts to relieve the pressure on the ED of patients awaiting their disposal. Patients awaiting admission may be put in a holding area, which is an area detached from the ED with own resources. This frees up beds in the ED for patients still needing treatment and the resource consumption of boarding patients is decreased. This concept is also introduced by Carmen et al. [26], Ferrin et al. [48] and Miller et al. [98].

The second buffer concept, an observation unit, is instituted for patients with an expected stay in the IUs of less than 24 hours and for patients needing observation before a discharge decision can be made. These patients are placed in an observation unit, instead of being admitted to the IUs. This limits the number of patients send to the already overburdened IUs, while eliminating unnecessary boarding, as an observation unit has separate resources [77, 26, 31, 119, 130].

A third buffer concept, a discharge lounge, focuses on discharged patients waiting to be picked up for transport out of the ED. By putting these patients in a separate room, ED capacity is freed up for newly incoming patients [48].

A few other improvements are introduced in addition to the buffer concepts. Kang et al. [70] look at the effect of altering the admission process policies, Alavi-Moghaddam et al. [6] and Eskandari et al. [46] increase the capacity to discharge patients home and Alavi-Moghaddam et al. [6], Bair et al. [13] and Pines et al. [107] investigate the effect of changing the number of boarding patients and the boarding time to quantify the impact of boarding on ED crowding.

*IU solutions*
Boarding is mainly caused by a capacity shortage in the IUs. Ferrin et al. [48] state that inpatient bottlenecks have the largest impact on ED performance and resolving them is an effective way to alleviate ED crowding. This is confirmed by Ben-Tovim et al. [17], who state that reducing problems at the end of the system significantly affects upstream processes such as ED boarding. The literature review of Carmen and Van Nieuwenhuyse [27] subdivides IU solutions into bed capacity, discharge policies and elective patient scheduling. Bed capacity is investigated, among others, by Ferrin et al. [48], Lane et al. [83], Miller et al. [98], Shi et al. [118] and Vanderby and Carter [128]. Eskandari et al. [46] suggest the addition of mobile beds, which can be switched between departments. Schneider et al. [116] investigate the reservation of IU beds for emergency patients and the effect of pooling beds between different IUs.

Next to a capacity shortage, a mismatch between the time of admissions and the time of discharges causes boarding. Planning discharges on IUs earlier in the day to match their timing with ED admissions, has the potential for a hospital to reduce ED crowding [98, 97, 118]. Wong et al. [143] enable weekend discharges to smooth IU discharges during the week. Ben-Tovim et al. [17] evaluate the effect of 24 hour a day discharges, eliminating administrative delays for IU discharges, and discharging patients in the IUs automatically after a LOS of 21 days to prevent long stay outliers. Gunal and Pidd [58], Miller et al. [97], Oh et al. [101] and Shi et al. [118] also shorten patient stays in the IUs to reduce patient turnaround time and waiting times for an IU bed.

The third IU solution method deals with elective patient scheduling. Vissers et al. [131] look at different strategies to schedule elective patients, with reserving a fixed capacity for ED admissions and planning elective patients in the other rooms being the most efficient strategy. Pines et al. [107] focus on cancellations of elective patients instead of the initial planning. The required percentage reduction in non-ED admissions to reach a 1 hour reduction of boarding time is defined. This reduction is implemented through both static (fixed number of cancellations per day) and dynamic (number of cancellations depends on hospital occupancy) cancellation policies.

*Collaborative solutions*
Collaborative solutions are most attractive, as these take both ED and IU considerations into account. However, collaboration is difficult to implement, as hospital units mostly work independently and focus on their own performance. Shi et al. [118] apply a routing policy for admitting ED patients to the IUs, taking boarding time into account. After reaching a specific threshold, other IUs than the preferred one are considered to keep boarding time within limits. This policy requires communication between the ED and IUs. A system-wide discharge strategy is examined by Crawford et al. [36]. In their study, IU patients are discharged earlier based on ED occupancy. Adan et al. [3] develop a scheduling algorithm, taking both emergency and elective patients into account, for an optimal allocation of the available resources throughout the hospital. Kang et al. [70] and Miller et al. [97] revise the admission process, enhancing collaboration between the ED and IUs.

### *4.4. Combinations of improvements*

An ED is a complex environment with various factors contributing to the crowding problem. The importance of a system-wide perspective is stressed by e.g. Mohiuddin et al. [99], Paul et al. [104] and Saghafian et al. [112]. As demographic factors, other healthcare facilities and inpatient units impact ED performance, an ED cannot be realistically analysed in isolation. Either the complete system should be modelled or important external effects should at least be included in a simplistic way. Besides external influences, the sequential processes that patients undergo in the ED are interdependent. Improvements in one step may impact patient flow in the previous or next step [68]. In the existing literature, little attention is given to these findings. Carmen et al. [26] analyse how different steps in patient flow through the ED influence each other. Interactions exist between improvements in one part of the ED and the performance of another part. For example, the introduction of buffer beds reduces boarding time in the output part, but increases wait-for-staff times in the throughput phase. Buffer beds lead to ED beds being occupied by care-intensive patients. As a result, demand for staff rises. If staff levels remain constant, their occupancy level increases and therefore also waiting times for staff [26]. Kadri et al. [68] find that equipment and staffing changes have a positive effect on waiting times and LOS, but only if they are introduced simultaneously because of the interdependence of sequential processes and resources. These findings indicate that interactions between consecutive processes and related KPIs have to be considered when analysing and optimising ED performance. Otherwise, suboptimal solutions will be found.

From Tables B.1 to B.3 it is clear that several researchers analyse multiple improvements. Nevertheless, the improvements are mostly situated within one phase of patient flow. In Figure 6, the percentage of articles considering only 1 improvement, multiple improvements separately and a combination of improvements is given. Of the reviewed literature, 25% considers only 1 improvement option. The most popular improvements in this category are triage interventions, patient streaming and staffing and scheduling. 35% analyses the effect of various improvement options, but separately. Most of the papers in this category include staffing and scheduling in their set of improvements, with 6 papers solely investigating improvements from this category. Equipment capacity changes and process/policy changes are also popular, but they are always investigated in combination with improvements from other categories. The remaining 40% of papers examines the effect of introducing multiple improvements simultaneously, which is the most interesting situation. This is not the majority of the papers, but still a fairly large proportion. Most papers in this category combine staffing and scheduling improvements with equipment capacity changes.

### *4.5. Research opportunities*

Several opportunities for future research exist. If we look at the individual improvement options, 58% of the papers introduce staffing changes. Around 30% of the papers look at equipment capacity and process/policy changes. All other categories are under investigated. As the category of process/policy changes is very broad, the individual improvements in this category are still rarely considered. Output improvements are an interesting area for future research, as boarding is seen as one of the main causes of ED crowding. Especially collaborative solutions should be investigated further, with only 5% of the papers introducing

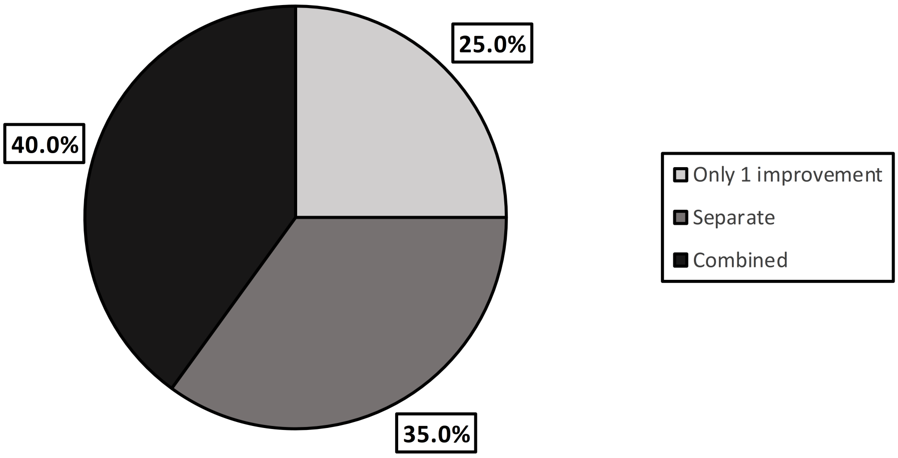



Figure 6: Proportional distribution of literature based on type of improvement combination

this type of improvement. This requires to acknowledge the link between EDs and IUs, and formulate system-wide solutions.

When examining the combinations of improvements, too many studies lack the inclusion of interactions present between the different operations in the ED. If multiple improvements are tested, their combination may give different results in comparison with a single improvement. Especially the effect of the joint introduction of throughput and output improvements on ED performance, is an interesting domain for future research. Only 8 papers investigate improvements in the throughput and output part of patient flow. Five of them examine the combined effect of improvements in the throughput and output part [26, 46, 48, 119, 101]. As reducing boarding may impact the throughput operations, and improving throughput operations may increase the number of boarding patients, this is an appealing combination. Another finding concerns the optimisation of ED performance by considering multiple improvement options in a simulation-optimisation context. Combined improvements are common practice in simulation-optimisation. Of the 14 simulation-optimisation papers, 12 papers introduce combined improvements. However, they only focus on staffing and scheduling, and equipment capacity. From these papers, 6 search for the optimal capacity of multiple human resource types [4, 23, 52, 59, 87, 138] and 5 optimise ED performance with regard to staff and equipment capacity [32, 47, 73, 86, 147]. Yeh and Lin [146] optimise nurse schedules instead of capacity. The application of simulation-optimisation to optimise ED performance with regard to other improvement options is an interesting domain for future research.

A final research opportunity deals with the KPIs used to evaluate the improvement options. As multiple improvements may cover several aspects of the ED, evaluating them based on a single KPI is difficult and can lead to incomplete or unreliable conclusions. So when a combination of improvements is considered, examining their effect based on multiple KPIs is highly recommended. Of the papers investigating the effect of a combination of improvements, 85% evaluate these improvements based on multiple KPIs. However, only 6 papers use a multi-objective approach [32, 33, 46, 47, 113, 139]. This indicates the lack of papers applying the preferred approach for both KPIs and improvement options, namely a multi-objective evaluation of the simultaneous introduction of multiple improvements.

## 5. The relation between KPIs and improvement options

### *5.1. Discussion*

In Sections 3 and 4, the reviewed literature is classified based on the investigated KPIs and improvement options. A wide variety of KPIs and improvement options exists and the majority of the reviewed papers considers multiple KPIs and improvement options. 85% of the papers takes multiple KPIs into consideration, while 75% tests the effect of more than one improvement option. This section gives an overview of the specific combinations of KPIs and improvement options present in the reviewed literature. For each combination, the amount of papers and an overall indication of the effect is given in Table C.1 in Appendix C.[1] Each cell in the table represents the combination of a specific improvement option and a specific KPI. The first number in each cell indicates the number of papers investigating the combination. The number between brackets is a compound indicator of the effect that the improvement option has on the KPI. A paper finding a positive effect of the improvement option on the KPI counts for +1, while a negative effect counts for -1. A positive effect means an upgrade of ED performance, and dependent on the specific KPI this means an increase or decrease. A negative effect is interpreted in the opposite direction. If no significant effect is found or the effect is not discussed in detail, the paper adds 0 to the compound indicator. This is also the case if multiple improvement options of a single category are tested and the results are contradicting, and when the KPIs are considered in both an objective function and constraints. The sum of all the individual effects gives an overall indication of the effect an improvement option has on a KPI, and this value is presented between brackets. If the combination is not investigated, a zero is present in the table.

In general, the table confirms the finding that LOS is the most popular KPI, while the use of qualitative, budget-related and IU KPIs is limited when analysing improvements. Given the drawbacks of qualitative KPIs and IU KPIs discussed in Section 3, the fact that these are lacking is not further discussed. The combination of throughput improvements with AD time is also lacking. Furthermore, the use of DTDT and LWBS is not in proportion to the importance attached to these KPIs in literature [51]. When focusing on the improvement options, staffing and scheduling is by far the most investigated category. For every KPI, it is the improvement option with the highest number of articles. As expected, the effect of staffing and scheduling improvements on LOS is the most frequent combination, present in 40 papers. A remarkable finding is the fact that for almost no combination general agreement exists on the effect an improvement option has on a KPI. In the next paragraph, the most important conclusions of Table C.1 are discussed per improvement option.

Triage interventions are mainly evaluated based on time-related KPIs (except boarding time), but findings on the effectiveness to improve these measures are diverse. The majority of papers concludes that triage interventions positively impact LOS, but waiting time is not significantly affected. A triage intervention has an impact on the priorities assigned to a patient, or accelerates the diagnosis and ordering of examinations (e.g. [9, 60, 62]). This mostly impacts one patient type positively, but has a negative impact on patients not favoured by the new triage system. The effect of triage interventions on utilisation and budget-related KPIs is not yet investigated. A possible reason is that triage interventions are thought to have no effect on the utilisation in consecutive processes, as they only impact priorities, and these improvements do not require large financial efforts.

The effect of patient streaming is also mainly examined for time-related measures. The compound indicator reveals that more researchers indicate a positive effect of patient streaming than of triage interventions. Nevertheless, the extent of the effect depends on the specific ED. Several researchers indicate that patient streaming only has a positive effect in a resource-constrained ED or the effect only applies to patient types affected by the streaming policy (e.g. low acuity patients in case of a fast track) [33, 35, 48, 81]. The investigation of utilisation and productivity, and budget-related KPIs is limited. Again, patient streaming has no large financial impact as it only consists of a reorganisation of the current ED. However, patient streaming can have an impact on utilisation, depending on the streaming rules or the assignment of resources to the different streams.

[1] A table with references of the specific papers in each category is available as online appendix.

Staffing and scheduling is the most prominent category of improvement options in ED simulation research, but the literature is not proportionally divided over the different KPIs. Regarding time-related KPIs, 40 papers introduce staffing and scheduling improvements in order to reduce LOS and 31 papers look at waiting times (i.e. 'other' time-related measures). Only one paper examines the influence of staffing and scheduling improvements on boarding time [101]. The effect on these measures is not always positive, depending on the specific ED and type of staffing improvement investigated. In one ED, for example, the addition of a physician has a positive effect, while an extra nurse has no effect because it is not the bottleneck resource (e.g. [82, 149]). In another ED, the opposite can be true. Besides, the allocation of the extra resource to a task or area has an impact on the extent of the improvement, which may be higher for the patient types making use of the extra resource [79]. Moreover, time-related measures are impacted by the interaction between processes and resources, and differ between patient types. Improving the capacity or scheduling of one type of resource may shift the bottleneck instead of resolving it, or may impact only a part of the patients in the ED [68]. The effect of staffing decisions on personnel utilisation is a third prevalent combination, with 21 papers. The fact that personnel utilisation is frequently analysed when considering staffing improvements is logical, and the effect is mostly positive. As the addition and rescheduling of staff can be budget intensive, most papers focus on the bottleneck resources [79]. Increasing their capacity reduces the high utilisation rate, which is positive. A possible explanation for the higher consistency in findings in comparison with the time-related measures, is the fact that utilisation rates are only impacted by the number of patients in the ED and the staff capacity. Budget-related KPIs are more frequently used than with other improvement options, but still underused given that staffing changes can have a direct financial impact. This seems contradicting based on the value of the compound indicator in the table. This value indicates no significant effect of staffing and scheduling decisions on costs. Sometimes costs are not allowed to increase significantly, in which case a budget restriction is imposed. Besides, the majority of papers taking cost into account apply a simulation-optimisation methodology in which costs are included in the constraints. The magnitude of the effect an improvement option has on costs is not deductible from these papers. Furthermore, the financial impact depends on the specific type of improvement.

Alterations of the equipment capacity are frequently suggested to improve ED performance. LOS is the most prevalent KPI to evaluate equipment capacity, followed by waiting time. In contrast to the previous improvement options, the largest part of papers investigating equipment capacity conclude that it has no or a negative effect. This can be explained by the fact that additional equipment is only beneficial if additional staff is employed to make this equipment operational [43]. In addition, the explanations from the previous paragraph are applicable, namely that only bottleneck resources have a significant impact, not all patient types benefit from additional equipment, and the problem is shifted to other parts of the patient flow [22, 48]. A notable finding is that all papers find a positive effect of equipment capacity on equipment utilisation. Except for one other combination discussed later, this is the only combination containing more than 3 papers where there is unanimity about the effect. Nonetheless, the analysis of this combination is infrequent given the direct relationship between equipment capacity and utilisation. As equipment is costly, too few papers consider budget-related KPIs. The compound indicator does not approve the financial impact of additional equipment, but the same explanations as with staffing and scheduling improvements are applicable.

The 'other' category contains process and policy changes, but the improvements are very diverse. As a result, a discussion of the link between this category of improvement options and the individual KPIs has little meaning.

Output improvements are less investigated than throughput improvements, although outflow is the major bottleneck in most EDs. ED solutions aim at improving the efficiency of the output processes that are under control of the ED. The KPIs adressed by these improvements are mainly time-related KPIs. No consistency exists between the researchers about the effect on time-related measures. Explanations found in literature are that the output process is only altered for part of the patients (e.g. only admitted patients) [119] and that the improvements should be combined with other adjustments, such as increased staffing [26]. Boarding time is only discussed in one paper, which is remarkable as boarding time is directly linked to the output process. DTDT is not considered in combination with output solutions in the ED. In addition to time-related KPIs, ED solutions are also linked with AD time, as an accelerated output process frees up place for new incoming patients [77, 107]. The use of utilisation and productivity KPIs is inadequate, since output improvements should relieve pressure on the ED and improve throughput. Otherwise, the improvements are not effective. Interesting is the negative impact on IU KPIs, indicating that facilitating outflow for admitted ED patients has a negative impact on elective patients [107]. The negative effect on costs implies that a better outflow in the ED requires a financial effort [46]. On the other hand, additional revenue can be generated [86, 107]. A trade-off exists between the financial investment and the resulting benefits. As a result, budget-related KPIs should be considered when evaluating ED solutions for the outflow problem.

IU solutions are capable of improving the outflow of admitted ED patients. All 7 papers examining the effect of IU solutions on ED LOS, describe a positive effect. For the other time-related KPIs, the large majority of papers also reports a positive effect. This confirms that reducing problems at the end of the system (i.e. the inpatient units) significantly affects upstream processes in the ED [17, 48, 118]. The relationship between IU solutions and AD time is not reported in the reviewed papers, and the use of utilisation and productivity measures is limited. As with ED solutions, IU solutions may be costly [46]. No significant positive effect on revenue is found, but only one paper considers this KPI [107]. IU KPIs are frequently used, and the solutions often have a positive impact on these performance measures. The findings suggest that IU solutions have the potential to increase both ED and IU performance.

The last category of improvement options are collaborative solutions. Since both the ED and IUs are involved in these improvement scenarios, these seem superior to pure ED and IU solutions. However, only 4 papers report on the effect of collaborative solutions on ED and IU performance [3, 36, 70, 118]. Collaborative solutions have no significant effect on patient satisfaction, but a negative effect on patient safety [36]. This negative effect is a result of discharging patients earlier, based on ED demand for inpatient beds. The few papers investigating time-related and proportions KPIs find a positive relationship. Papers investigating the effect of collaborative solutions on utilisation and productivity, and budget-related KPIs are lacking. As collaborative solutions impact both the ED and IU, and IU KPIs are only included in one paper, this is insufficient.

*5.2. Research opportunities*

The zero fields in Table C.1 indicate that multiple combinations of KPIs and improvement options have not been investigated in previous research. These combinations provide opportunities for future research. However, not all these combinations are equally relevant. The effect of triage interventions, patient streaming, and output improvements on personnel and equipment utilisation, and budget-related KPIs may be interesting. The effect of output improvements on DTDT can also be informing. On the other hand, qualitative research into the effect of improvement options on patient safety and patient satisfaction can only provide useful insights to hospital managers if these KPIs can be estimated objectively. The combinations with AD time and IU KPIs are also less relevant. However, in countries where AD is current practice, identifying ways to reduce AD from within the ED may be worthwhile given the negative consequences of this procedure.

In addition to the relations that are not yet investigated, some promising combinations with only a limited amount of papers become apparent from Table C.1. First of all, boarding is one of the main causes of ED crowding and all studies that include boarding time as KPI to evaluate improvement options report a positive effect [17, 26, 36, 97, 101, 130]. Both throughput and output improvements can effectively reduce boarding. The further examination of improvement options (both throughput and output improvements) to reduce boarding time is thus an interesting area for future research. Secondly, personnel utilisation is frequently investigated in combination with staffing and scheduling improvements, but it is less used as KPI to evaluate other types of improvements. Nonetheless, personnel utilisation is an important KPI from the viewpoint of ED staff and it is directly related to ED crowding [18, 99]. The relation between personnel utilisation and triage interventions, patient streaming [135], equipment capacity changes (e.g. [1, 41, 101]) and output improvements [46, 83, 101] should be investigated more thoroughly. Thirdly, the use of patient throughput with patient streaming [105] and output solutions [86, 101, 107] is currently overlooked. Fourthly, all improvements that are not directly linked to budget-related KPIs are not considered in combination with them, while they may have an effect. Additional staff or equipment, the introduction of buffer zones or the addition of IU beds has a direct financial impact. However, other improvements may result in more patients treated within the same time period, less AD, fewer patients leaving the ED without being seen by a physician or lower personnel or equipment requirements. This has in turn a positive financial influence on the ED. A final finding is the relatively limited use of DTDT in comparison with LOS, given that DTDT is highly relevant for critical patients and LOS for low acuity patients.

Finally, little consensus is found in current literature on the effect of improvement options on the different KPIs (discrepancy between number of papers and effect size in Table C.1). No general agreement exists for most combinations that are examined in multiple papers. The problem is most apparent for combinations with time-related KPIs. This is remarkable since these are the combinations most often used in literature. Additional research to define the specific relation between improvement options and KPIs can be valuable for all combinations with inconsistent results. Furthermore, it can be beneficial to determine the circumstances under which a specific relation is valid. Large differences exist between EDs worldwide, and depending on the context the effect may be positive, negative or insignificant.

## 6. Conclusion and future research opportunities

This literature review structures the scientific literature on ED simulation based on KPIs and improvement options. In addition to a discussion of the individual KPIs and improvement options, combinations present in the literature are detected for both. The two aspects of this literature review are linked by investigating the relationship between KPIs and improvement options. Structuring the literature can provide guidance to researchers and practitioners when deciding on the KPIs and improvement options to consider, and reveal promising areas for future research.

As ED crowding has become a major international problem, operations research techniques have been widely applied to analyse and optimise ED operations. The focus of this literature review is on simulation techniques. Simulation enables to capture the randomness and complexity of patient flow at the level of an individual patient, making this technique particularly suitable for modelling and analysing emergency departments. As a result, simulation studies will cover the widest range of KPIs, improvement options and combinations of them. The features of simulation also make this technique most suitable to investigate multiple KPIs and improvement options simultaneously. Because this paper provides a comprehensive review of KPIs, improvement options and their relations, it is plausible to focus on simulation studies. If the objective is to optimise ED performance in addition to analysing it, the interesting features of simulation may be combined with optimisation methods by use of simulation-optimisation techniques. The application of simulation-optimisation is rather scarce in existing research, but the technique is promising for application in future research.

When analysing the ED crowding problem, deciding upon the appropriate KPIs to measure ED performance is crucial. An overview and discussion on ED KPIs is provided in Section 3 and the tables in Appendix A. Qualitative as well as quantitative KPIs exist, with quantitative KPIs being the largest group in the reviewed literature because of their objectivity. Quantitative KPIs can be divided into time-related, proportions, utilisation and productivity, and budget-related KPIs. Time-related KPIs are commonly used as measure of ED performance, with length of stay being the most used KPI (65% of the reviewed papers). Other categories are less investigated, and budget-related KPIs are even underused given their practical importance when implementing solutions. As all KPIs have their advantages and disadvantages, and covering all aspects of ED performance within one measure is impossible, a combination of KPIs is more representative. Of the reviewed literature, over 85% considers more than one KPI in their analysis of ED operations. However, only 11% of these apply a multi-objective approach with the simultaneous analysis and/or optimisation of multiple KPIs.

Based on the selected KPIs, ED operations are evaluated and improvements are suggested in the literature. These improvements can be situated in the input, throughput or output part of an ED. Section 4 and the tables in Appendix B contain an overview of the improvement options present in the reviewed literature. Existing literature mainly focuses on throughput improvements, while the input and output part of patient flow are the greatest bottlenecks in practice. Improvements with regard to staffing and scheduling are most common, with 58% of the papers analysing improvements in this category. Combinations of improvements are superior to single improvements. Especially improvements in both the throughput and output part should be considered simultaneously. 75% of the reviewed papers investigate more than one improvement option, but only 40% of them look at the effect of simultaneously introducing multiple improvements.

The integration of the discussions on KPIs and improvement options, which is provided in Section 5 and Table C.1 of Appendix C, gives an indication of the specific combinations of KPIs and improvement options present in the reviewed literature. In addition, the effectiveness of improvement options to ameliorate specific KPIs is indicated. Time-related KPIs are widely used to evaluate improvement options, while utilisation and productivity measures, and budget-related KPIs are underused. A general finding is that consensus on the effect that an improvement option has on a KPI is lacking for nearly all combinations. When deciding which combination of improvement options and KPIs to consider, the characteristics of the ED under study should be taken into account. The large differences within the literature suggest that the effect of an improvement option differs based on the specific context. Output improvements have great potential to improve ED performance, while the benefits of throughput improvements are more questionable and situation-dependent. This indicates that improvement options in the throughput phase should be adapted to the specific situation and not investigated in isolation, because of the interdependency of the sequential processes a patient undergoes in the ED. Additionally, a specific improvement option may have a positive effect on one KPI, but a negative effect on another. This confirms the importance of a multi-objective approach and the introduction of combined improvements. Combining improvements makes it possible to fully exploit the potential benefits of the single improvement options.

The OR literature on ED performance is extensive, but several opportunities for future research exist. Firstly, the combination of KPIs in a multi-objective way to analyse and optimise ED performance with simulation techniques is an interesting topic for future research. As a result of the small amount of literature on this subject, various combinations of KPIs are not considered in a multi-objective context. Also, there are some methodological opportunities. As multi-objective research is scarce in an ED context, not all methodological possibilities are already explored. Only three studies construct a Pareto front in order to solve the multi-objective problem, and some well-known multi-objective methods have not been applied in an ED simulation context.

Secondly, in addition to the combination of KPIs, the simultaneous introduction of multiple improvements provides opportunities for future research. Too many studies lack the inclusion of interactions between the different operations in the ED, leading to suboptimal decision making. If interactions are not taken into account, combined improvements are considered unnecessary. An important point for future research is the modelling of the complete ED in order to get more reliable results. When modelling the complete ED, various opportunities exist for future research with regard to the simultaneous improvement of multiple processes in the ED. Especially the joint introduction of improvements throughout the different parts of patient flow, for example throughput and output improvements, is an interesting research domain. Furthermore, new improvement options or combinations of improvements not yet investigated can be formulated and tested. The integration of combined improvements with a multi-objective approach is another research area in which little has been done. An important consideration in deciding upon the number of KPIs and improvement options is the computation time. As simulation is a time-consuming technique, a trade-off has to be made between the problem size (i.e. number of output measures and scenarios) and the desired precision of simulation results. As a result, methodological challenges exist in order to efficiently deal with this characteristic of simulation.

Thirdly, several gaps are identified in existing literature regarding combinations of KPIs and improvement options. First of all, improvements have to be adapted to the specific context in order to improve ED performance. Secondly, utilisation and productivity KPIs are under investigated, except for improvement options directly impacting these measures like increasing staff or equipment capacity. As decreasing high utilisation rates in the ED is a prerequisite to improve patient flow, these measures should be included more frequently. In addition, utilisation rates focus on caregivers, while time-related measures are patient-centred. Improvement options should benefit all types of stakeholders in the ED to facilitate a successful implementation. This makes budget-related KPIs also crucial from the viewpoint of hospital managers. The limited number of papers investigating these KPIs suggest that improvement options can have a significant impact on both costs and revenue, so these KPIs should be included more frequently. Fourthly, most combinations with boarding time are only once investigated. Since boarding time is a main cause of ED crowding, the relation between both throughput and output improvements, and boarding time, is an interesting area for future research. A final important finding is that the output improvements have a mostly positive effect on almost all KPIs, both in the ED and inpatient units. Output improvements have great potential to alleviate crowding, but confirmation of the findings is necessary given the limited number of papers. Examining the effect of output improvements on the different KPIs more thoroughly can be worthwhile.

Fourthly, simulation-optimisation is a promising research domain. This technique is not often applied and, consequently, the use of a multi-objective approach or the simultaneous introduction of multiple improvements is not frequently investigated. Most simulation-optimisation literature optimises ED performance based on only one KPI, with the inclusion of other KPIs in the constraints. A multi-objective approach in combination with simulation-optimisation is only twice applied in the reviewed literature. Concerning improvement options, only the optimal staffing and scheduling configuration and equipment capacity are examined. The introduction of other improvements, and the joint introduction of throughput and output improvements, is an interesting domain for future simulation-optimisation research, as this has proven to be effective in a simulation context.

This literature review focuses on ED simulation studies, but other OR techniques (e.g. queuing theory) have been used to analyse and optimise ED operations. As these techniques also have interesting characteristics that may be beneficial under certain circumstances, a comprehensive literature review on the KPIs and improvement options used in these studies is a final interesting research opportunity. Additionally, a comparison of the characteristics of ED studies applying different OR techniques may provide useful insights for future ED research.

**Appendix A. Tables Key Performance Indicators**

Table A.1: Key Performance Indicators - Single KPI

| Reference | ED KPIs | | | | | | | | | | | | | | | IU KPIs | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Quali -tative | | Quantitative | | | | | | | | | | | | | Quali -tative | Quantitative | | | | | |
| | | | Time-related | | | | Proportions | | | Utilisation & productivity | | | | Budget-related | | | Time-related | | Proportions | | Utilisation & productivity | |
| | Patient satisfaction | Patient safety | LOS | DTDT | Boarding time | Other | AD time | LWBS | Other | Personnel utilisation | Equipment utilisation | Patient throughput | Other | Costs | Revenue | Patient satisfaction | LOS | Other | Elective cancellations | Other | Hospital occupancy | Other |
| Batarseh et al. [15] | | | | | x | | | | | | | | | | | | | | | | | |
| Borgman et al. [21] | | | | | x | | | | | | | | | | | | | | | | | |
| El-Rifai et al. [45] | | | | | | | | x | | | | | | | | | | | | | | |
| Gunal and Pidd [55] | | | | | x | | | | | | | | | | | | | | | | | |
| Kang et al. [70] | | | | | x | | | | | | | | | | | | | | | | | |
| Khare et al. [74] | | | | | x | | | | | | | | | | | | | | | | | |
| Liu et al. [89] | | | | | x | | | | | | | | | | | | | | | | | |
| Mahapatra et al. [91] | | | | | | | | x | | | | | | | | | | | | | | |
| Maull et al. [92] | | | | | | | | | | | x | | | | | | | | | | | |
| Miller et al. [98] | | | | | x | | | | | | | | | | | | | | | | | |
| Pines et al. [108] | | | x | | | | | | | | | | | | | | | | | | | |
| Ruohonen et al. [111] | | | | | x | | | | | | | | | | | | | | | | | |
| Takakuwa and Shiozaki [123] | | | | | | | | x | | | | | | | | | | | | | | |
| Vanderby and Carter [128] | | | | | x | | | | | | | | | | | | | | | | | |
| Weng et al. [138] | | | | | | | | | | | | | | | x | | | | | | | |
| Yeh and Lin [146] | | | | | | | | x | | | | | | | | | | | | | | |

Table A.2: Key Performance Indicators - Separate analysis

| Reference | ED KPIs | | | | | | | | | | | | | | | IU KPIs | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Quali -tative | | Quantitative | | | | | | | | | | | | | Quali -tative | Quantitative | | | | | | |
| | | | Time-related | | | | Proportions | | | Utilisation & productivity | | | | Budget-related | | | Time-related | | Proportions | | Utilisation & productivity | | |
| | Patient satisfaction | Patient safety | LOS | DTDT | Boarding time | Other | AD time | LWBS | Other | Personnel utilisation | Equipment utilisation | Patient throughput | Other | Costs | Revenue | Patient satisfaction | LOS | Other | Elective cancellations | Other | Hospital occupancy | Other | |
| Alavi-Moghaddam et al. [6] | | | | | x | | | x | | | | | | | | | | | | | | | |
| Ashour and Okudan Kremer [9] | | | | | x | | | x | | | x | | | x | | | | | | | | | |
| Ashour and Okudan Kremer [10] | | | | x | x | | | x | | | x | | | x | | | | | | | | | |
| Bair et al. [13] | | | | | | | | | | x | | | | | x | | | | | | | | |
| Bal et al. [14] | | | | | x | | | x | | | | x | | | | | | | | | | | |
| Ben-Tovim et al. [17] | | | | | | | x | x | | | | | | | | | | | | | | x | |
| Brenner et al. [22] | | | | | x | | | x | | | | x | x | x | | | | | | | | | |
| Carmen et al. [25] | | | | | x | | x | | | | | | | | | | | | | | | | |
| Carmen et al. [26] | | | | | x | | x | x | | | | | | | | | | | | | | | |
| Ceglowski et al. [28] | | | | | x | x | | x | | | | | | | | | | | | | | | |
| Centeno et al. [29] | | | | | x | x | | | | | | | | x | | | | | | | | | |
| Chavis et al. [31] | | | | | | | | x | | | | | x | | | | | | | | | | |
| Choon et al. [34] | | | | | x | x | | | | | | | | | | | | | | | | | |
| Connelly [35] | | | | | x | | | x | | | | | | | | | | | | | | | |
| Davies [37] | | | | | x | | | x | | | x | | | | | | | | | | | | |
| Day et al. [38] | | | | | x | | | | | | x | | | | | | | | | | | | |
| Duguay and Chetouane [43] | | | | | x | | | x | | | | | x | x | | | | | | | | | |
| Eatock et al. [44] | | | | | x | | | | | | x | | | | | | | | | | | | |
| Ferrin et al. [48] | | | | | x | | | | x | x | x | | | | | | | | | | | | |
| Gul and Guneri [53] | | | | | x | | | x | | | | x | x | x | | | | | | | | | |
| Gunal and Pidd [56] | | | | | x | | | | | | x | | | | | | | | | | | | |
| Gunal and Pidd [58] | | | | | | | | | | | | | | | | | | | x | x | x | x | x |
| Holm and Dahl [60] | | | | | x | | | x | | | | | | | | | | | | | | | |
| Hopp et al. [62] | | | | x | x | | | | | | | | | | | | | | | | | | |
| Hussein et al. [64] | | | | | x | | | | | | | | x | | x | | | | | | | | |
| Ismail et al. [65] | | | x | | | | | x | | x | x | x | x | | x | | | | | | | | |
| Izady and Worthington [66] | | | | | x | | | x | | | x | x | | | | | | | | | | | |

| Reference | ED KPIs | | | | | | | | | | | | | | | IU KPIs | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Quali -tative | | Quantitative | | | | | | | | | | | | | Quali -tative | Quantitative | | | | | |
| | | | Time-related | | | | Proportions | | | Utilisation & productivity | | | | Budget-related | | | Time-related | | Proportions | | Utilisation & productivity | |
| | Patient satisfaction | Patient safety | LOS | DTDT | Boarding time | Other | AD time | LWBS | Other | Personnel utilisation | Equipment utilisation | Patient throughput | Other | Costs | Revenue | Patient satisfaction | LOS | Other | Elective cancellations | Other | Hospital occupancy | Other |
| Kadri et al. [68] | | | | | x | | | x | | | | | | | | | | | | | | |
| Kang and Lobo [69] | | | | | x | x | | | | | | | | | | | | | | | | |
| Kaushal et al. [71] | | | | | x | x | | | | | | | | | | | | | | | | |
| Khurma et al. [75] | | | | | | | | x | | | | x | | | x | | | | | | | |
| Kolb et al. [76] | | | | | | x | x | | | | | | | | x | | | | | | | x |
| Kolb et al. [77] | | | | | | | | x | x | | | | | | | | | | | | | x |
| Komashie and Mousavi [79] | | | | | x | | | x | | | | x | | | | | | | | | | |
| Konrad et al. [80] | | | | | x | x | | | | | | | | | | | | | | | | |
| Kuo et al. [82] | | | | | | x | | | | | | x | | | | | | | | | | |
| Kuo et al. [81] | | | | | | | | x | | | | x | | | x | | | | | | | |
| Lane et al. [83] | | | | | | x | | x | | | | x | | | | | | | | x | | x |
| Laskowski and Mukhi [84] | | | | | | | | x | | | | x | | | x | | | | | | | |
| Lin et al. [88] | | | | | | | | x | | | x | | | | x | | | | | | | |
| Macdonald et al. [90] | | | | | x | | | x | | x | | | | x | | | | | | | | |
| Medeiros et al. [94] | | | | | x | x | | x | | x | | | | | x | | | | | | | |
| Meng and Spedding [95] | | | | | x | | | x | | | | | | | x | | | | | | | |
| Miller et al. [97] | | | | | x | | x | | | x | | | | | | | | | | | | |
| Oh et al. [101] | | | | | x | | x | x | | x | | x | x | x | | | | | | | | |
| Paul and Lin [103] | | | | | x | | | | | | | x | x | x | | | | | | | | |
| Peck and Kim [105] | | | | | | | | x | | | | | | x | | | | | | | | |
| Pines et al. [107] | | | | | | | | | x | x | | | | x | | x | | | | x | | |
| Rachuba et al. [109] | | | | | x | | | | | | | | | | x | | | | | | | |
| Rado et al. [110] | | | | | | | | x | | | | x | | | | | | | | | | |
| Samaha et al. [115] | | | | | x | | | x | | | | x | | x | x | | | | | | | |
| Schneider et al. [116] | | | | | | | | | | | | | | | | | | | x | | x | x |
| Sengupta et al. [117] | | | | | | | | x | | | | x | | | | | | | | | | |
| Shi et al. [118] | | | | | | | | x | | | x | | | | x | | | | | | | x |
| Shim and Kumar [119] | | | | | | | | x | | | | | | | | | | | | | | |
| Sinreich and Jabali [120] | | | | | x | | | | | | | x | | | | | | | | | | |

| Reference | ED KPIs | | | | | | | | | | | | | | | IU KPIs | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Quali-tative | | Quantitative | | | | | | | | | | | | | Quali-tative | Quantitative | | | | | |
| | | | Time-related | | | | Proportions | | | Utilisation & productivity | | | | Budget-related | | | Time-related | | Proportions | | Utilisation & productivity | |
| | Patient satisfaction | Patient safety | LOS | DTDT | Boarding time | Other | AD time | LWBS | Other | Personnel utilisation | Equipment utilisation | Patient throughput | Other | Costs | Revenue | Patient satisfaction | LOS | Other | Elective cancellations | Other | Hospital occupancy | Other |
| Sinreich et al. [121] | | | x | | | x | | | | x | | | | | | | | | | | | |
| Vile et al. [130] | | | x | | x | | | | | | | | | | | | | | | | | |
| Vissers et al. [131] | | | | | | | | | x | | | | | | | | | x | x | | | |
| Wang [134] | | | x | x | | x | | x | | | | | | | | | | | | | | |
| Wang et al. [135] | | | | | | x | | | | x | | | x | | | | | | | | | |
| Wang et al. [133] | | | x | | | | | | | x | | | | | | | | | | | | |
| Wang et al. [132] | | | x | | | x | | | x | | | | x | | | | | | | | | |
| Wong et al. [143] | | | x | | | | | | | | | | x | | | | x | | | | | x |
| Wong et al. [144] | | | x | x | | x | | | x | | | | | | | | | | | | | |
| Yang et al. [145] | | | x | x | | | | | | | | | | | | | | | | | | |
| Zeltyn et al. [148] | | | x | | | | | | x | x | | | x | | | | | | | | | |
| Zeng et al. [149] | | | x | | | x | | x | | x | x | | | | | | | | | | | |

Table A.3: Key Performance Indicators - Single objective with constraints

| Reference | ED KPIs | | | | | | | | | | | | | | | | IU KPIs | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Quali -tative | | Quantitative | | | | | | | | | | | | | | Quali -tative | Quantitative | | | | | |
| | | | Time-related | | | | Proportions | | | Utilisation & productivity | | | | Budget-related | | | | Time-related | | Proportions | | Utilisation & productivity | |
| | Patient satisfaction | Patient safety | LOS | DTDT | Boarding time | Other | AD time | LWBS | Other | Personnel utilisation | Equipment utilisation | Patient throughput | Other | Costs | Revenue | | Patient satisfaction | LOS | Other | Elective cancellations | Other | Hospital occupancy | Other |
| Ahmed and Alkhamis [4] | | | | | | | | x | | | | | | x | | x | | | | | | | |
| Beck et al. [16] | | | | | x | | | | | | | | | | | | x | | | | | | |
| Cabrera et al. [23] | | | | | x | | | | | | | | | | | x | | | | | | | |
| Centeno et al. [30] | | | | | x | | | | | | | | | | | x | | | | | | | |
| Diefenbach and Kozan [41] | | | | | | x | | x | | | x | x | x | | | | | | | | | | |
| Ghanes et al. [52] | | | | | x | x | | | | | | | | | | x | | | | | | | |
| Guo et al. [59] | | | | | x | | | x | | | | | | | | x | | | | | | | |
| Keshtkar et al. [73] | | | | | x | | | x | | | | x | x | | | x | | | | | | | |
| Lee et al. [86] | | | | x | x | | | x | | x | | x | x | x | x | | x | | | | | | |
| Lee et al. [87] | | | | | | | | x | | | | | | | | x | x | | | | | | |
| Zeinali et al. [147] | | | | | | | | x | | | | | | | | x | | | | | | | |

Table A.4: Key Performance Indicators - Multi-objective

| Reference | ED KPIs | | | | | | | | | | | | | | | IU KPIs | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Quali -tative | | Quantitative | | | | | | | | | | | | | Quali -tative | Quantitative | | | | | |
| | | | Time-related | | | | Proportions | | | Utilisation & productivity | | | | Budget-related | | | Time-related | | Proportions | | Utilisation & productivity | |
| | Patient satisfaction | Patient safety | LOS | DTDT | Boarding time | Other | AD time | LWBS | Other | Personnel utilisation | Equipment utilisation | Patient throughput | Other | Costs | Revenue | Patient satisfaction | LOS | Other | Elective cancellations | Other | Hospital occupancy | Other |
| **Scalarization/Weighted sum** | | | | | | | | | | | | | | | | | | | | | | |
| Abo-Hamad and Arisha [1] | | | x | x | | | | x | | x | x | | x | | | | | | | | | |
| Chonde et al. [33] | | | x | x | | | | | | | | | | | | | | | | | | |
| Eskandari et al. [46] | | | | | | x | | | | x | x | | | x | | | | | | | x | |
| Saghafian et al. [113] | | | x | x | | | | | | | | | | | | | | | | | | |
| **Goal programming** | | | | | | | | | | | | | | | | | | | | | | |
| Adan et al. [3] | x | | | | | | | | | | | | | | | x | | | | | | x |
| Jerbi and Kamoun [67] | | | x | | | x | | | | x | | x | | | | | | | | | | |
| **Metaheuristics** | | | | | | | | | | | | | | | | | | | | | | |
| Chen and Wang [32] | | | x | | | | | | | | | | | x | | | | | | | | |
| Feng et al. [47] | | | x | | | | | | | | | | | x | | | | | | | | |
| **Data envelopment analysis** | | | | | | | | | | | | | | | | | | | | | | |
| Al-Refaie et al. [5] | | | x | | | | | | | x | | x | | | | | | | | | | |
| Weng et al. [139] | | | | | | x | | | | x | | | | | | | | | | | | |
| **Graphical analysis** | | | | | | | | | | | | | | | | | | | | | | |
| Crawford et al. [36] | | x | | | x | x | x | x | | | | | | | | | | | | | | |
| Kolker [78] | | | x | | | x | x | | | | | | x | | | | | | | | | |

## Appendix B. Tables improvement options

Table B.1: Improvement options - Single improvement

| Reference | Improvement options | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Throughput | | | | | Output | | |
| | Triage interventions | Patient streaming | Staffing and scheduling | Equipment capacity | Other | ED solutions | IU solutions | Collaborative solutions |
| Adan et al. [3] | | | | | | | | x |
| Ashour and Okudan Kremer [9] | x | | | | | | | |
| Ashour and Okudan Kremer [10] | x | | | | | | | |
| Bair et al. [13] | | | | | | x | | |
| Centeno et al. [30] | | | x | | | | | |
| Chavis et al. [31] | | | | | | x | | |
| Connelly [35] | | x | | | | | | |
| Crawford et al. [36] | | | | | | | | x |
| Davies [37] | | x | | | | | | |
| Eatock et al. [44] | | x | | | | | | |
| El-Rifai et al. [45] | | | x | | | | | |
| Holm and Dahl [60] | x | | | | | | | |
| Izady and Worthington [66] | | | x | | | | | |
| Kolb et al. [76] | | | | | x | | | |
| Kuo et al. [81] | | x | | | | | | |
| Lane et al. [83] | | | | | | | x | |
| Mahapatra et al. [91] | | | | | x | | | |
| Maull et al. [92] | | x | | | | | | |
| Medeiros et al. [94] | | x | | | | | | |
| Peck and Kim [105] | | x | | | | | | |
| Rachuba et al. [109] | | | | | x | | | |
| Ruohonen et al. [111] | x | | | | | | | |
| Vissers et al. [131] | | | | | | | x | |
| Wong et al. [143] | | | | | | | x | |
| Yeh and Lin [146] | | | x | | | | | |

Table B.2: Improvement options - Separate analysis

| Reference | Improvement options | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Throughput | | | | | Output | | |
| | Triage interventions | Patient streaming | Staffing and scheduling | Equipment capacity | Other | ED solutions | IU solutions | Collaborative solutions |
| Abo-Hamad and Arisha [1] | | | x | x | x | | | |
| Alavi-Moghaddam et al. [6] | | | x | x | | x | | |
| Al-Refaie et al. [5] | | | x | | | | | |

| Reference | Improvement options | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Throughput | | | | | Output | | |
| | Triage interventions | Patient streaming | Staffing and scheduling | Equipment capacity | Other | ED solutions | IU solutions | Collaborative solutions |
| Beck et al. [16] | | | x | x | x | | | |
| Ben-Tovim et al. [17] | | | | | | | x | |
| Brenner et al. [22] | | | x | x | | | | |
| Centeno et al. [29] | | | x | | x | | | |
| Choon et al. [34] | | | x | x | x | | | |
| Diefenbach and Kozan [41] | | | x | x | | | | |
| Gunal and Pidd [55] | | | x | x | x | | | |
| Ismail et al. [65] | | | x | x | | | | |
| Jerbi and Kamoun [67] | | | x | | | | | |
| Kang et al. [70] | | | | | | x | x | x |
| Kaushal et al. [71] | | x | | | | | | |
| Khare et al. [74] | | | | | | x | | |
| Komashie and Mousavi [79] | | | x | x | x | | | |
| Kuo et al. [82] | | | x | | | | | |
| Laskowski and Mukhi [84] | | | x | | | | | |
| Lee et al. [86] | | | x | | x | x | | |
| Macdonald et al. [90] | x | | x | x | x | | | |
| Miller et al. [98] | | | | | x | x | x | |
| Miller et al. [97] | | | | | x | | x | x |
| Rado et al. [110] | | | x | | | | | |
| Samaha et al. [115] | | x | x | x | x | | | |
| Sengupta et al. [117] | | | x | | x | | | |
| Shi et al. [118] | | | | | | | x | x |
| Vanderby and Carter [128] | | | | | x | | x | |
| Vile et al. [130] | | x | | | | x | | |
| Wang [134] | | | x | | x | | | |
| Wang et al. [135] | | x | | | x | | | |
| Wang et al. [133] | | | x | x | x | | | |
| Wang et al. [132] | | | x | | | | | |
| Wong et al. [144] | | | x | | x | | | |
| Zeltyn et al. [148] | | | x | | x | | | |
| Zeng et al. [149] | | | x | x | | | | |

Table B.3: Improvement options - Combined analysis

| Reference | Improvement options | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Throughput | | | | | Output | | |
| | Triage interventions | Patient streaming | Staffing and scheduling | Equipment capacity | Other | ED solutions | IU solutions | Collaborative solutions |
| Ahmed and Alkhamis [4] | | | x | | | | | |
| Bal et al. [14] | | | x | | x | | | |

| Reference | Improvement options | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Throughput | | | | | Output | | |
| | Triage interventions | Patient streaming | Staffing and scheduling | Equipment capacity | Other | ED solutions | IU solutions | Collaborative solutions |
| Batarseh et al. [15] | | x | x | | x | | | |
| Borgman et al. [21] | x | | x | x | x | | | |
| Cabrera et al. [23] | | | x | | | | | |
| Carmen et al. [26] | | | x | x | | x | | |
| Chen and Wang [32] | | | x | x | | | | |
| Chonde et al. [33] | | x | x | | | | | |
| Day et al. [38] | x | | x | | | | | |
| Duguay and Chetouane [43] | | | x | x | | | | |
| Eskandari et al. [46] | | | | x | x | x | x | |
| Feng et al. [47] | | | x | x | | | | |
| Ferrin et al. [48] | | x | x | x | x | x | x | |
| Ghanes et al. [52] | | | x | | | | | |
| Gul and Guneri [53] | | | x | | | | | |
| Gunal and Pidd [58] | | | | | | | x | |
| Guo et al. [59] | | | x | | | | | |
| Hussein et al. [64] | | | | | x | | | |
| Hopp et al. [62] | x | x | | | | | | |
| Kadri et al. [68] | | | x | x | | | | |
| Kang and Lobo [69] | | | | x | x | | | |
| Keshtkar et al. [73] | | | x | x | | | | |
| Khurma et al. [75] | | | x | | x | | | |
| Kolb et al. [77] | | | | | | x | | |
| Konrad et al. [80] | x | x | x | | | | | |
| Lee et al. [87] | | | x | | | | | |
| Meng and Spedding [95] | | | | x | x | | | |
| Oh et al. [101] | | | x | x | x | | x | |
| Paul and Lin [103] | | | x | x | x | | | |
| Pines et al. [107] | | | | | | x | x | |
| Saghafian et al. [113] | x | x | | | | | | |
| Shim and Kumar [119] | | | | | x | x | | |
| Sinreich and Jabali [120] | | | x | | | | | |
| Sinreich et al. [121] | | | x | | | | | |
| Schneider et al. [116] | | | | | | | x | |
| Takakuwa and Shiozaki [123] | | | x | x | | | | |
| Weng et al. [138] | | | x | | | | | |
| Weng et al. [139] | | | x | x | | | | |
| Yang et al. [145] | x | | x | x | | | | |
| Zeinali et al. [147] | | | x | x | | | | |

## Appendix C. Table relations between KPIs and improvement options

Table C.1: Relations between KPIs and improvement options

| Effect | | | | Improvement options | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Throughput | | | | | Output | | |
| | | | | Triage interventions | Patient streaming | Staffing & scheduling | Equipment capacity | Other | ED solutions | IU solutions | Collaborative solutions |
| ED KPIs | Qualitative | | Patient satis-faction | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 (0) |
| | | | Patient safety | 2 (+2) | 1 (+1) | 1 (+1) | 0 | 1 (+1) | 1 (+1) | 0 | 1 (-1) |
| | Quantitative | Time-related | LOS | 11 (+4) | 13 (+7) | 40 (+25) | 23 (+8) | 24 (+15) | 7 (+4) | 7 (+7) | 1 (+1) |
| | | | DTDT | 3 (+2) | 5 (+4) | 9 (+5) | 4 (+2) | 3 (0) | 0 | 1 (0) | 0 |
| | | | Boarding time | 0 | 1 (+1) | 1 (+1) | 1 (+1) | 1 (+1) | 1 (+1) | 3 (+3) | 1 (+1) |
| | | | Other | 4 (0) | 6 (+4) | 31 (+18) | 17 (+8) | 13 (+7) | 7 (+3) | 5 (+4) | 2 (+2) |
| | | Proportions | AD time | 0 | 0 | 0 | 0 | 0 | 2 (+2) | 0 | 1 (+1) |
| | | | LWBS | 1 (+1) | 1 (+1) | 6 (+5) | 5 (+3) | 3 (+1) | 2 (+2) | 2 (+2) | 0 |
| | | | Other | 3 (+2) | 4 (+1) | 5 (+4) | 1 (+1) | 3 (+3) | 0 | 2 (+1) | 1 (+1) |
| | | Utilisation & productivity | Personnel utilization | 0 | 2 (0) | 21 (+15) | 6 (+3) | 9 (+7) | 1 (+1) | 3 (+1) | 0 |
| | | | Equipment utilization | 0 | 0 | 6 (+4) | 6 (+6) | 4 (+2) | 2 (+1) | 2 (+1) | 0 |
| | | | Patient throughput | 3 (+1) | 1 (+1) | 11 (+6) | 5 (+2) | 5 (+4) | 2 (+2) | 1 (+1) | 0 |
| | | | Other | 0 | 3 (+2) | 8 (+7) | 3 (+2) | 9 (+9) | 2 (+2) | 2 (+2) | 1 (+1) |

| Effect | | Improvement options | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Throughput | | | | | Output | | |
| | | Triage interventions | Patient streaming | Staffing & scheduling | Equipment capacity | Other | ED solutions | IU solutions | Collaborative solutions |
| Budget-related | Costs | 0 | 0 | 9 (+1) | 5 (0) | 1 (0) | 1 (-1) | 1 (-1) | 0 |
| | Revenue | 0 | 0 | 3 (0) | 1 (0) | 2 (+1) | 2 (+2) | 1 (0) | 0 |
| IU KPIs | | 0 | 0 | 0 | 1 (0) | 1 (0) | 3 (-1) | 8 (+6) | 1 (0) |

## References


[1] Abo-Hamad W, Arisha A. Simulation-based framework to improve patient experience in an emergency department. European Journal of Operational Research 2013;224(1):154–66. doi:10.1016/j.ejor.2012.07.028.

[2] ACEP . Crowding (policy statement). https://www.acep.org/practres.aspx?id=29156; 2006.

[3] Adan I, Bekkers J, Dellaert N, Jeunet J, Vissers J. Improving operational effectiveness of tactical master plans for emergency and elective patients under stochastic demand and capacitated resources. European Journal of Operational Research 2011;213(1):290–308. doi:10.1016/j.ejor.2011.02.025.

[4] Ahmed MA, Alkhamis TM. Simulation optimization for an emergency department healthcare unit in Kuwait. European Journal of Operational Research 2009;198(3):936–42. doi:10.1016/j.ejor.2008.10.025.

[5] Al-Refaie A, Fouad RH, Li MH, Shurrab M. Applying simulation and DEA to improve performance of emergency department in a Jordanian hospital. Simulation Modelling Practice and Theory 2014;41:59–72. doi:10.1016/j.simpat.2013.11.010.

[6] Alavi-Moghaddam M, Forouzanfar R, Alamdari S, Shahrami A, Kariman H, Amini A, Pourbabaee S, Shirvani A. Application of Queuing Analytic Theory to Decrease Waiting Times in Emergency Department: Does it Make Sense? Archives of Trauma Research 2012;1(3):101–7. doi:10.5812/atr.7177.

[7] Amaral TM, Costa AP. Improving decision-making and management of hospital resources: An application of the PROMETHEE II method in an Emergency Department. Operations Research for Health Care 2014;3(1):1–6. doi:10.1016/j.orhc.2013.10.002.

[8] Aringhieri R, Bruni M, Khodaparasti S, van Essen J. Emergency medical services and beyond: Addressing new challenges through a wide literature review. Computers & Operations Research 2017;78:349–68. doi:10.1016/j.cor.2016.09.016.

[9] Ashour OM, Okudan Kremer GE. A simulation analysis of the impact of FAHPMAUT triage algorithm on the Emergency Department performance measures. Expert Systems with Applications 2013;40(1):177–87. doi:10.1016/j.eswa.2012.07.024.

[10] Ashour OM, Okudan Kremer GE. Dynamic patient grouping and prioritization: a new approach to emergency department flow improvement. Health Care Management Science 2016;19(2):192–205. doi:10.1007/s10729-014-9311-1.

[11] Asplin BR, Magid DJ, Rhodes KV, Solberg LI, Lurie N, Camargo CA. A conceptual model of emergency department crowding. Annals of Emergency Medicine 2003;42(2):173–80. doi:10.1067/mem.2003.302.

[12] Avalosse H, Chapelle A, van Sloten F. Toevlucht tot de spoeddienst van een ziekenhuis: exploratie van de gegevens van cm. CM report healthcare consumption; 2015.

[13] Bair AE, Song WT, Chen YC, Morris BA. The Impact of Inpatient Boarding on ED Efficiency: A Discrete-Event Simulation Study. Journal of Medical Systems 2010;34(5):919–29. doi:10.1007/s10916-009-9307-4.

[14] Bal A, Ceylan C, Taolu C. Using value stream mapping and discrete event simulation to improve efficiency of emergency departments. International Journal of Healthcare Management 2017;10(3):196–206. doi:10.1080/20479700.2017.1304323.

[15] Batarseh OG, Goldlust EJ, Day TE. SysML for conceptual modeling and simulation for analysis: a case example of a highly granular model of an emergency department. In: Simulation Conference (WSC), 2013 Winter. IEEE; 2013. p. 2398–409.

[16] Beck E, Balasubramanian H, Henneman PL. Resource management and process change in a simplified model of the emergency department. IEEE; 2009. p. 1887–95. doi:10.1109/WSC.2009.5429198.

[17] Ben-Tovim D, Filar J, Hakendorf P, Qin S, Thompson C, Ward D. Hospital Event Simulation Model: Arrivals to DischargeDesign, development and application. Simulation Modelling Practice and Theory 2016;68:80–94. doi:10.1016/j.simpat.2016.07.004.

[18] Bergs J, Vandijck D, Hoogmartens O, Heerinckx P, Van Sassenbroeck D, Depaire B, Marneffe W, Verelst S. Emergency department crowding: Time to shift the paradigm from predicting and controlling to analysing and managing. International Emergency Nursing 2016;24:74–7. doi:10.1016/j.ienj.2015.05.004.

[19] Bergs J, Verelst S, Gillet JB, Deboutte P, Vandoren C, Vandijck D. The number of patients simultaneously present at the emergency department as an indicator of unsafe waiting times: A receiver operated curve-based evaluation. International Emergency Nursing 2014;22(4):185–9. doi:10.1016/j.ienj.2014.01.002.

[20] Bhattacharjee P, Ray PK. Patient flow modelling and performance analysis of healthcare delivery processes in hospitals: A review and reflections. Computers & Industrial Engineering 2014;78:299–312. doi:10.1016/j.cie.2014.04.016.

[21] Borgman NJ, Mes MR, Vliegen IM, Hans EW. Improving the design and operation of an integrated emergency post via simulation. Journal of simulation 2015;9(2):99–110.

[22] Brenner S, Zeng Z, Liu Y, Wang J, Li J, Howard PK. Modeling and Analysis of the Emergency Department at University of Kentucky Chandler Hospital Using Simulations. Journal of Emergency Nursing 2010;36(4):303–10. doi:10.1016/j.jen.2009.07.018.

[23] Cabrera E, Taboada M, Iglesias ML, Epelde F, Luque E. Simulation Optimization for Healthcare Emergency Departments. Procedia Computer Science 2012;9:1464–73. doi:10.1016/j.procs.2012.04.161.

[24] Caramia M, Dell' Olmo P. Multi-objective optimization. Multi-objective management in freight logistics: Increasing capacity, service level and safety with optimization algorithms 2008;:11–36.

[25] Carmen R, Defraeye M, Celik Aydin B, Van Nieuwenhuyse I. Modeling emergency departments using discrete-event simulation: A real-life case study including patient boarding 2014;.

[26] Carmen R, Defraeye M, Van Nieuwenhuyse I. A Decision Support System for Capacity Planning in Emergency Departments. International Journal of Simulation Modelling 2015;14(2):299–312. doi:10.2507/IJSIMM14(2)10.308.

[27] Carmen R, Van Nieuwenhuyse I. Improving patient flow in emergency departments with OR techniques: a literature overview; 2014.

[28] Ceglowski R, Churilov L, Wasserthiel J. Combining Data Mining and Discrete Event Simulation for a value-

added view of a hospital emergency department. Journal of the Operational Research Society 2007;58(2):246–54. doi:10.1057/palgrave.jors.2602270.
[29] Centeno AP, Martin R, Sweeney R. REDSim: A spatial agent-based simulation for studying emergency departments. In: Simulation Conference (WSC), 2013 Winter. IEEE; 2013. p. 1431–42.
[30] Centeno MA, Giachetti R, Linn R, Ismail AM. Emergency departments II: a simulation-ilp based tool for scheduling ER staff. In: Proceedings of the 35th conference on Winter simulation: driving innovation. Winter Simulation Conference; 2003. p. 1930–8.
[31] Chavis J, Cochran AL, Kocher KE, Washington VN, Zayas-Cabn G. A simulation model of patient flow through the emergency department to determine the impact of a short stay unit on hospital congestion. In: Proceedings of the 2016 Winter Simulation Conference. IEEE Press; 2016. p. 1982–93.
[32] Chen TL, Wang CC. Multi-objective simulation optimization for medical capacity allocation in emergency department. Journal of Simulation 2016;10(1):50–68. doi:10.1057/jos.2014.39.
[33] Chonde S, Parra C, Chang CJ. Minimizing flow-time and time-to-first-treatment in an emergency department through simulation. In: Proceedings of the 2013 Winter Simulation Conference: Simulation: Making Decisions in a Complex World. IEEE Press; 2013. p. 2374–85.
[34] Choon OH, Dali Z, Beng PT, Magdalene CPY. Uncovering effective process improvement strategies in an emergency department using discrete event simulation. Health Systems 2014;3(2):93–104.
[35] Connelly LG. Discrete Event Simulation of Emergency Department Activity: A Platform for System-level Operations Research. Academic Emergency Medicine 2004;11(11):1177–85. doi:10.1197/j.aem.2004.08.021.
[36] Crawford EA, Parikh PJ, Kong N, Thakar CV. Analyzing Discharge Strategies during Acute Care: A Discrete-Event Simulation Study. Medical Decision Making 2014;34(2):231–41. doi:10.1177/0272989X13503500.
[37] Davies R. See and Treat or See and Treat in an emergency department. In: Simulation Conference, 2007 Winter. IEEE; 2007. p. 1519–22.
[38] Day TE, Al-Roubaie AR, Goldlust EJ. Decreased length of stay after addition of healthcare provider in emergency department triage: a comparison between computer-simulated and real-world interventions. Emergency Medicine Journal 2013;30(2):134–8. doi:10.1136/emermed-2012-201113.
[39] Defraeye M, Van Nieuwenhuyse I. Staffing and scheduling under nonstationary demand for service: A literature review. Omega 2016;58:4–25. doi:10.1016/j.omega.2015.04.002.
[40] Deo S, Gurvich I. Centralized vs. Decentralized Ambulance Diversion: A Network Perspective. SSRN Electronic Journal 2011;doi:10.2139/ssrn.1619419.
[41] Diefenbach M, Kozan E. Effects of bed configurations at a hospital emergency department. Journal of Simulation 2011;5(1):44–57. doi:10.1057/jos.2010.1.
[42] Downey LVA, Zun LS. Determinates of Throughput Times in the Emergency Department. Journal of Health Management 2007;9(1):51–8. doi:10.1177/097206340700900103.
[43] Duguay C, Chetouane F. Modeling and Improving Emergency Department Systems using Discrete Event Simulation. SIMULATION 2007;83(4):311–20. doi:10.1177/0037549707083111.
[44] Eatock J, Clarke M, Picton C, Young T. Meeting the fourhour deadline in an A&E department. Journal of Health Organization and Management 2011;25(6):606–24. doi:10.1108/14777261111178510.
[45] El-Rifai O, Garaix T, Augusto V, Xie X. A stochastic optimization model for shift scheduling in emergency departments. Health Care Management Science 2015;18(3):289–302. doi:10.1007/s10729-014-9300-4.
[46] Eskandari H, Riyahifard M, Khosravi S, Geiger CD. Improving the emergency department performance using simulation and MCDM methods. In: Simulation Conference (WSC), Proceedings of the 2011 Winter. IEEE; 2011. p. 1211–22.
[47] Feng YY, Wu IC, Chen TL. Stochastic resource allocation in emergency departments with a multi-objective simulation optimization algorithm. Health Care Management Science 2017;20(1):55–75. doi:10.1007/s10729-015-9335-1.
[48] Ferrin D, Miller M, McBroom D. Maximizing hospital finanacial impact and emergency department throughput with simulation. IEEE; 2007. p. 1566–73. doi:10.1109/WSC.2007.4419774.
[49] Forster AJ. The Effect of Hospital Occupancy on Emergency Department Length of Stay and Patient Disposition. Academic Emergency Medicine 2003;10(2):127–33. doi:10.1197/aemj.10.2.127.
[50] Geiderman JM, Marco CA, Moskop JC, Adams J, Derse AR. Ethics of ambulance diversion. The American Journal of Emergency Medicine 2015;33(6):822–7. doi:10.1016/j.ajem.2014.12.002.
[51] Ghanes K, Diakogiannis A, Jouini O, Jemai Z, Wargon M. Key performance indicators for emergency departments: A survey from an operations management perspective. Technical Report; Working Paper, Ecole Centrale Paris; 2014.
[52] Ghanes K, Wargon M, Jouini O, Jemai Z, Diakogiannis A, Hellmann R, Thomas V, Koole G. Simulation-based optimization of staffing levels in an emergency department. SIMULATION 2015;91(10):942–53. doi:10.1177/0037549715606808.
[53] Gul M, Guneri AF. A computer simulation model to reduce patient length of stay and to improve resource utilization rate in an emergency department service system. International Journal of Industrial Engineering 2012;19(5):221–31.
[54] Gul M, Guneri AF. A comprehensive review of emergency department simulation applications for normal and disaster conditions. Computers & Industrial Engineering 2015;83:327–44. doi:10.1016/j.cie.2015.02.018.
[55] Gunal MM, Pidd M. Understanding accident and emergency department performance using simulation. In: Proceedings of the 38th conference on Winter simulation. Winter Simulation Conference; 2006. p. 446–52.
[56] Gunal MM, Pidd M. Understanding target-driven action in emergency department performance using simulation. Emergency Medicine Journal 2009;26(10):724–7. doi:10.1136/emj.2008.066969.
[57] Gunal MM, Pidd M. Discrete event simulation for performance modelling in health care: a review of the literature. Journal of Simulation 2010;4(1):42–51. doi:10.1057/jos.2009.25.
[58] Gunal MM, Pidd M. DGHPSIM:: Generic simulation of hospital performance. ACM Transactions on Modeling and

Computer Simulation 2011;21(4):1–22. doi:10.1145/2000494.2000496.
[59] Guo H, Gao S, Tsui KL, Niu T. Simulation Optimization for Medical Staff Configuration at Emergency Department in Hong Kong. IEEE Transactions on Automation Science and Engineering 2017;14(4):1655–65. doi:10.1109/TASE.2017.2697899.
[60] Holm LB, Dahl FA. Simulating the effect of physician triage in the emergency department of Akershus University Hospital. In: Winter Simulation Conference. Winter Simulation Conference; 2009. p. 1896–905.
[61] Hoot NR, Aronsky D. Systematic Review of Emergency Department Crowding: Causes, Effects, and Solutions. Annals of Emergency Medicine 2008;52(2):126–136.e1. doi:10.1016/j.annemergmed.2008.03.014.
[62] Hopp WJ, Desmond JS, Saghafian S, Van Oyen MP, Kronick SL. Complexity-Augmented Triage: A Tool for Improving Patient Safety and Operational Efficiency 2013;.
[63] Hosseinifard SZ, Abbasi B, Minas JP. Intensive care unit discharge policies prior to treatment completion. Operations Research for Health Care 2014;3(3):168–75. doi:10.1016/j.orhc.2014.06.001.
[64] Hussein NA, Abdelmaguid TF, Tawfik BS, Ahmed NG. Mitigating overcrowding in emergency departments using Six Sigma and simulation: A case study in Egypt. Operations Research for Health Care 2017;15:1–12. doi:10.1016/j.orhc.2017.06.003.
[65] Ismail K, Abo-Hamad W, Arisha A. Integrating balanced scorecard and simulation modeling to improve Emergency Department performance in Irish hospitals. IEEE; 2010. p. 2340–51. doi:10.1109/WSC.2010.5678931.
[66] Izady N, Worthington D. Setting staffing requirements for time dependent queueing networks: The case of accident and emergency departments. European Journal of Operational Research 2012;219(3):531–40. doi:10.1016/j.ejor.2011.10.040.
[67] Jerbi B, Kamoun H. Using simulation and goal programming to reschedule emergency department doctors shifts: case of a Tunisian hospital. Journal of Simulation 2009;3(4):211–9. doi:10.1057/jos.2009.6.
[68] Kadri F, Chaabane S, Tahon C. A simulation-based decision support system to prevent and predict strain situations in emergency department systems. Simulation Modelling Practice and Theory 2014;42:32–52. doi:10.1016/j.simpat.2013.12.004.
[69] Kang H, Lobo JM. Identifying the optimal configuration of an express care area in an emergency department: a DES and metamodeling approach. In: Winter Simulation Conference (WSC), 2016. IEEE; 2016. p. 1961–9.
[70] Kang H, Nembhard HB, Rafferty C, DeFlitch CJ. Patient Flow in the Emergency Department: A Classification and Analysis of Admission Process Policies. Annals of Emergency Medicine 2014;64(4):335–342.e8. doi:10.1016/j.annemergmed.2014.04.011.
[71] Kaushal A, Zhao Y, Peng Q, Strome T, Weldon E, Zhang M, Chochinov A. Evaluation of fast track strategies using agent-based simulation modeling to reduce waiting time in a hospital emergency department. Socio-Economic Planning Sciences 2015;50:18–31. doi:10.1016/j.seps.2015.02.002.
[72] Kelton WD, Sadowski RP, Zupick NB. Simulation with Arena. 6th ed. New York, NY: McGraw-Hill Education, 2015.
[73] Keshtkar L, Salimifard K, Faghih N. A simulation optimization approach for resource allocation in an emergency department. QScience Connect 2015;2015(1):8. doi:10.5339/connect.2015.8.
[74] Khare RK, Powell ES, Reinhardt G, Lucenti M. Adding More Beds to the Emergency Department or Reducing Admitted Patient Boarding Times: Which Has a More Significant Influence on Emergency Department Congestion? Annals of Emergency Medicine 2009;53(5):575–585.e2. doi:10.1016/j.annemergmed.2008.07.009.
[75] Khurma N, Bacioiu GM, Pasek ZJ. Simulation-based verification of lean improvement for emergency room process. In: Proceedings of the 40th conference on winter simulation. Winter Simulation Conference; 2008. p. 1490–9.
[76] Kolb EM, Lee T, Peck J. Effect of coupling between emergency department and inpatient unit on the overcrowding in emergency departmetn. In: 2007 Winter simulation conference. IEEE; 2007. p. 1586–93.
[77] Kolb EM, Schoening S, Peck J, Lee T. Reducing emergency department overcrowding: five patient buffer concepts in comparison. In: Proceedings of the 40th conference on winter simulation. Winter Simulation Conference; 2008. p. 1516–25.
[78] Kolker A. Process Modeling of Emergency Department Patient Flow: Effect of Patient Length of Stay on ED Diversion. Journal of Medical Systems 2008;32(5):389–401. doi:10.1007/s10916-008-9144-x.
[79] Komashie A, Mousavi A. Modeling emergency departments using discrete event simulation techniques. In: Proceedings of the 37th conference on Winter simulation. Winter Simulation Conference; 2005. p. 2681–5.
[80] Konrad R, DeSotto K, Grocela A, McAuley P, Wang J, Lyons J, Bruin M. Modeling the impact of changing patient flow processes in an emergency department: Insights from a computer simulation study. Operations Research for Health Care 2013;2(4):66–74. doi:10.1016/j.orhc.2013.04.001.
[81] Kuo YH, Leung JM, Graham CA, Tsoi KK, Meng HM. Using simulation to assess the impacts of the adoption of a fast-track system for hospital emergency services. Journal of Advanced Mechanical Design, Systems, and Manufacturing 2018;12(3):JAMDSM0073–. doi:10.1299/jamdsm.2018jamdsm0073.
[82] Kuo YH, Rado O, Lupia B, Leung JMY, Graham CA. Improving the efficiency of a hospital emergency department: a simulation study with indirectly imputed service-time distributions. Flexible Services and Manufacturing Journal 2016;28(1-2):120–47. doi:10.1007/s10696-014-9198-7.
[83] Lane DC, Monefeldt C, Rosenhead JV. Looking in the Wrong Place for Healthcare Improvements: A System Dynamics Study of an Accident and Emergency Department. The Journal of the Operational Research Society 2000;51(5):518. doi:10.2307/254183.
[84] Laskowski M, Mukhi S. Agent-based simulation of emergency departments with patient diversion. In: International Conference on Electronic Healthcare. Springer; 2008. p. 25–37.
[85] Law AM. Simulation Modeling and Analysis. McGraw-Hill, 2007.
[86] Lee EK, Atallah HY, Wright MD, Post ET, Thomas C, Wu DT, Haley LL. Transforming Hospital Emergency Department

Workflow and Patient Care. Interfaces 2015;45(1):58–82. doi:10.1287/inte.2014.0788.
[87] Lee ML, Park I, Park DU, Park C. Constrained Ranking and Selection for Operations of an Emergency Department. International Journal of Simulation Modelling 2016;16(4):563–75. doi:10.2507/IJSIMM16(4)1.388.
[88] Lin CH, Kao CY, Huang CY. Managing emergency department overcrowding via ambulance diversion: A discrete event simulation model. Journal of the Formosan Medical Association 2015;114(1):64–71. doi:10.1016/j.jfma.2012.09.007.
[89] Liu Z, Rexachs D, Epelde F, Luque E. An agent-based model for quantitatively analyzing and predicting the complex behavior of emergency departments. Journal of Computational Science 2017;21:11–23. doi:10.1016/j.jocs.2017.05.015.
[90] Macdonald SJ, Karkam I, Al-Shiwarri N, Chowdhary RJ, Escalante EM, Afandi A. Emergency department process improvement. In: Systems and Information Engineering Design Symposium, 2005 IEEE. IEEE; 2005. p. 253–62.
[91] Mahapatra S, Koelling CP, Patvivatsiri L, Fraticelli B, Eitel D, Grove L. Pairing emergency severity index5-level triage data with computer aided system design to improve emergency department access and throughput. In: Winter Simulation Conference. volume 2; 2003. p. 1917–25.
[92] Maull RS, Smart PA, Harris A, Karasneh AAF. An evaluation of fast track in A&E: a discrete event simulation approach. The Service Industries Journal 2009;29(7):923–41. doi:10.1080/02642060902749534.
[93] McCarthy ML, Zeger SL, Ding R, Aronsky D, Hoot NR, Kelen GD. The Challenge of Predicting Demand for Emergency Department Services. Academic Emergency Medicine 2008;15(4):337–46. doi:10.1111/j.1553-2712.2008.00083.x.
[94] Medeiros DJ, Swenson E, DeFlitch C. Improving patient flow in a hospital emergency department. In: Proceedings of the 40th conference on winter simulation. Winter Simulation Conference; 2008. p. 1526–31.
[95] Meng YL, Spedding T. Modelling patient arrivals when simulating an accident and emergency unit. In: Simulation Conference, 2008. WSC 2008. Winter. IEEE; 2008. p. 1509–15.
[96] Miettinen K. Introduction to multiobjective optimization: Noninteractive approaches. In: Multiobjective Optimization. Springer; 2008. p. 1–26.
[97] Miller M, Ferrin D, Shahi N. Estimating patient surge impact on boarding time in several regional emergency departments. In: Winter Simulation Conference. Winter Simulation Conference; 2009. p. 1906–15.
[98] Miller MJ, Ferrin DM, Szymanski JM. Emergency departments II: simulating Six Sigma improvement ideas for a hospital emergency department. In: Proceedings of the 35th conference on Winter simulation: driving innovation. Winter Simulation Conference; 2003. p. 1926–9.
[99] Mohiuddin S, Busby J, Savovi J, Richards A, Northstone K, Hollingworth W, Donovan JL, Vasilakis C. Patient flow within UK emergency departments: a systematic review of the use of computer simulation modelling methods. BMJ Open 2017;7(5):e015007. doi:10.1136/bmjopen-2016-015007.
[100] Moskop JC, Sklar DP, Geiderman JM, Schears RM, Bookman KJ. Emergency Department Crowding, Part 1:Concept, Causes, and Moral Consequences. Annals of Emergency Medicine 2009;53(5):605–11. doi:10.1016/j.annemergmed.2008.09.019.
[101] Oh C, Novotny AM, Carter PL, Ready RK, Campbell DD, Leckie MC. Use of a simulation-based decision support tool to improve emergency department throughput. Operations Research for Health Care 2016;9:29–39. doi:10.1016/j.orhc.2016.03.002.
[102] Oredsson S, Jonsson H, Rognes J, Lind L, Gransson KE, Ehrenberg A, Asplund K, Castrn M, Farrohknia N. A systematic review of triage-related interventions to improve patient flow in emergency departments. Scandinavian Journal of Trauma, Resuscitation and Emergency Medicine 2011;19(1):43. doi:10.1186/1757-7241-19-43.
[103] Paul JA, Lin L. Models for Improving Patient Throughput and Waiting at Hospital Emergency Departments. The Journal of Emergency Medicine 2012;43(6):1119–26. doi:10.1016/j.jemermed.2012.01.063.
[104] Paul SA, Reddy MC, DeFlitch CJ. A Systematic Review of Simulation Studies Investigating Emergency Department Overcrowding. SIMULATION 2010;86(8-9):559–71. doi:10.1177/0037549710360912.
[105] Peck JS, Kim SG. Improving patient flow through axiomatic design of hospital emergency departments. CIRP Journal of Manufacturing Science and Technology 2010;2(4):255–60. doi:10.1016/j.cirpj.2010.04.003.
[106] Pham JC, Patel R, Millin MG, Kirsch TD, Chanmugam A. The Effects of Ambulance Diversion: A Comprehensive Review. Academic Emergency Medicine 2006;13(11):1220–7. doi:10.1197/j.aem.2006.05.024.
[107] Pines JM, Batt RJ, Hilton JA, Terwiesch C. The Financial Consequences of Lost Demand and Reducing Boarding in Hospital Emergency Departments. Annals of Emergency Medicine 2011;58(4):331–40. doi:10.1016/j.annemergmed.2011.03.004.
[108] Pines JM, Iyer S, Disbot M, Hollander JE, Shofer FS, Datner EM. The Effect of Emergency Department Crowding on Patient Satisfaction for Admitted Patients. Academic Emergency Medicine 2008;15(9):825–31. doi:10.1111/j.1553-2712.2008.00200.x.
[109] Rachuba S, Knapp K, Ashton L, Pitt M. Streamlining pathways for minor injuries in emergency departments through radiographer-led discharge. Operations Research for Health Care 2018;19:44–56. doi:10.1016/j.orhc.2018.03.001.
[110] Rado O, Lupia B, Leung JM, Kuo YH, Graham CA. Using simulation to analyze patient flows in a hospital emergency department in Hong Kong. In: Proceedings of the International Conference on Health Care Systems Engineering. Springer; 2014. p. 289–301.
[111] Ruohonen T, Neittaanmki P, Teittinen J. Simulation model for improving the operation of the emergency department of special health care. In: Proceedings of the 38th conference on Winter simulation. Winter Simulation Conference; 2006. p. 453–8.
[112] Saghafian S, Austin G, Traub SJ. Operations research/management contributions to emergency department patient flow optimization: Review and research prospects. IIE Transactions on Healthcare Systems Engineering 2015;5(2):101–23. doi:10.1080/19488300.2015.1017676.
[113] Saghafian S, Hopp WJ, Van Oyen MP, Desmond JS, Kronick SL. Patient Streaming as a Mechanism for Improving

Responsiveness in Emergency Departments. Operations Research 2012;60(5):1080–97. doi:10.1287/opre.1120.1096.
[114] Salmon A, Rachuba S, Briscoe S, Pitt M. A structured literature review of simulation modelling applied to Emergency Departments: Current patterns and emerging trends. Operations Research for Health Care 2018;doi:10.1016/j.orhc.2018.01.001.
[115] Samaha S, Armel WS, Starks DW. Emergency departments I: the use of simulation to reduce the length of stay in an emergency department. In: Proceedings of the 35th conference on Winter simulation: driving innovation. Winter Simulation Conference; 2003. p. 1907–11.
[116] Schneider TAJ, Besselink LP, Zonderland ME, Boucherie RJ, van den Hout WB, Kievit J, Bilars P, Fogteloo AJ, Rabelink TJ. Allocating Emergency Beds Improves the Emergency Admission Flow. Interfaces 2018;48(4):384–94. doi:10.1287/inte.2018.0951.
[117] Sengupta S, Deneweth M, Van Til RP. A better approach to modeling emergency care service. In: Proceedings of the winter simulation conference. Winter Simulation Conference; 2011. p. 1202–10.
[118] Shi P, Chou MC, Dai JG, Ding D, Sim J. Models and Insights for Hospital Inpatient Operations: Time-Dependent ED Boarding Time. Management Science 2015;:150422112841002doi:10.1287/mnsc.2014.2112.
[119] Shim SJ, Kumar A. Simulation for emergency care process reengineering in hospitals. Business Process Management Journal 2010;16(5):795–805. doi:10.1108/14637151011076476.
[120] Sinreich D, Jabali O. Staggered work shifts: a way to downsize and restructure an emergency department workforce yet maintain current operational performance. Health Care Management Science 2007;10(3):293–308. doi:10.1007/s10729-007-9021-z.
[121] Sinreich D, Jabali O, Dellaert NP. Reducing emergency department waiting times by adjusting work shifts considering patient visits to multiple care providers. IIE Transactions 2012;44(3):163–80. doi:10.1080/0740817X.2011.609875.
[122] Sinreich D, Marmor Y. Emergency department operations: the basis for developing a simulation tool. IIE transactions 2005;37(3):233–45.
[123] Takakuwa S, Shiozaki H. Functional analysis for operating emergency department of a general hospital. In: Simulation Conference, 2004. Proceedings of the 2004 Winter. IEEE; volume 2; 2004. p. 2003–11.
[124] Tang C, Chen Y, Lee S. Non-clinical work counts: facilitating patient outflow in an emergency department. Behaviour & Information Technology 2015;34(6):585–97. doi:10.1080/0144929X.2014.963673.
[125] US Department of Health and Human Services . Health, united states, 2015 - with special features on racial and ethnic health disparities. DHHS Publication No. 2016-1232; 2016.
[126] Van Bockstal E, Maenhout B. A study on the impact of prioritising emergency department arrivals on the patient waiting time. Health Care Management Science 2018;doi:10.1007/s10729-018-9447-5.
[127] Vanbrabant L, Martin N, Ramaekers K, Braekers K. Quality of input data in emergency department simulations: Framework and assessment techniques. Simulation Modelling Practice and Theory 2019;91:83–101. doi:10.1016/j.simpat.2018.12.002.
[128] Vanderby S, Carter MW. An evaluation of the applicability of system dynamics to patient flow modelling. Journal of the Operational Research Society 2010;61(11):1572–81. doi:10.1057/jors.2009.150.
[129] Velasquez M, Hester PT. An analysis of multi-criteria decision making methods. International Journal of Operations Research 2013;10(2):56–66.
[130] Vile JL, Allkins E, Frankish J, Garland S, Mizen P, Williams JE. Modelling patient flow in an emergency department to better understand demand management strategies. Journal of Simulation 2017;11(2):115–27. doi:10.1057/s41273-016-0004-2.
[131] Vissers JM, Adan IJ, Dellaert NP. Developing a platform for comparison of hospital admission systems: An illustration. European Journal of Operational Research 2007;180(3):1290–301. doi:10.1016/j.ejor.2006.04.034.
[132] Wang B, McKay K, Jewer J, Sharma A. Physician shift behavior and its impact on service performances in an emergency department. IEEE; 2013. p. 2350–61. doi:10.1109/WSC.2013.6721610.
[133] Wang J, Li J, Tussey K, Ross K. Reducing Length of Stay in Emergency Department: A Simulation Study at a Community Hospital. IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans 2012;42(6):1314–22. doi:10.1109/TSMCA.2012.2210204.
[134] Wang L. An agent-based simulation for workflow in emergency department. In: Systems and Information Engineering Design Symposium, 2009. SIEDS'09. IEEE; 2009. p. 19–23.
[135] Wang T, Guinet A, Belaidi A, Besombes B. Modelling and simulation of emergency services with ARIS and Arena. Case study: the emergency department of Saint Joseph and Saint Luc Hospital. Production Planning & Control 2009;20(6):484–95. doi:10.1080/09537280902938605.
[136] Welch S, Augustine J, Camargo CA, Reese C. Emergency Department Performance Measures and Benchmarking Summit. Academic Emergency Medicine 2006;13(10):1074–80. doi:10.1197/j.aem.2006.05.026.
[137] Welch SJ, Stone-Griffith S, Asplin B, Davidson SJ, Augustine J, Schuur JD, on behalf of The Second Performance Measures and Benchmarking Summit and the Emergency Department Benchmarking Alliance . Emergency Department Operations Dictionary: Results of the Second Performance Measures and Benchmarking Summit: ED OPERATIONS DICTIONARY. Academic Emergency Medicine 2011;18(5):539–44. doi:10.1111/j.1553-2712.2011.01062.x.
[138] Weng SJ, Cheng BC, Kwong ST, Wang LM, Chang CY. Simulation optimization for emergency department resources allocation. In: Simulation Conference (WSC), Proceedings of the 2011 Winter. IEEE; 2011. p. 1231–8.
[139] Weng SJ, Tsai BS, Wang LM, Chang CY, Gotcher D. Using simulation and data envelopment analysis in optimal healthcare efficiency allocations. In: Simulation Conference (WSC), Proceedings of the 2011 Winter. IEEE; 2011. p. 1295–305.
[140] Wiler JL, Gentle C, Halfpenny JM, Heins A, Mehrotra A, Mikhail MG, Fite D. Optimizing Emergency Department

Front-End Operations. Annals of Emergency Medicine 2010;55(2):142–160.e1. doi:10.1016/j.annemergmed.2009.05.021.

[141] Wiler JL, Griffey RT, Olsen T. Review of Modeling Approaches for Emergency Department Patient Flow and Crowding Research: MODELING APPROACHES FOR ED PATIENT FLOW AND CROWDING RESEARCH. Academic Emergency Medicine 2011;18(12):1371–9. doi:10.1111/j.1553-2712.2011.01135.x.

[142] Wiler JL, Welch S, Pines J, Schuur J, Jouriles N, Stone-Griffith S. Emergency Department Performance Measures Updates: Proceedings of the 2014 Emergency Department Benchmarking Alliance Consensus Summit. Academic Emergency Medicine 2015;22(5):542–53. doi:10.1111/acem.12654.

[143] Wong HJ, Wu RC, Caesar M, Abrams H, Morra D. Smoothing inpatient discharges decreases emergency department congestion: a system dynamics simulation model. Emergency Medicine Journal 2010;27(8):593–8. doi:10.1136/emj.2009.078543.

[144] Wong ZSY, Lit ACH, Leung SY, Tsui KL, Chin KS. A discrete-event simulation study for emergency room capacity management in a Hong Kong hospital. In: Winter Simulation Conference (WSC), 2016. IEEE; 2016. p. 1970–81.

[145] Yang KK, Lam SSW, Low JM, Ong MEH. Managing emergency department crowding through improved triaging and resource allocation. Operations Research for Health Care 2016;10:13–22. doi:10.1016/j.orhc.2016.05.001.

[146] Yeh J, Lin W. Using simulation technique and genetic algorithm to improve the quality care of a hospital emergency department. Expert Systems with Applications 2007;32(4):1073–83. doi:10.1016/j.eswa.2006.02.017.

[147] Zeinali F, Mahootchi M, Sepehri MM. Resource planning in the emergency departments: A simulation-based metamodeling approach. Simulation Modelling Practice and Theory 2015;53:123–38. doi:10.1016/j.simpat.2015.02.002.

[148] Zeltyn S, Lauterman T, Schwartz D, Moskovitch K, Tzafrir S, Basis F, Marmor YN, Mandelbaum A, Carmeli B, Greenshpan O, Mesika Y, Wasserkrug S, Vortman P, Shtub A. Simulation-based models of emergency departments:: Operational, tactical, and strategic staffing. ACM Transactions on Modeling and Computer Simulation 2011;21(4):1–25. doi:10.1145/2000494.2000497.

[149] Zeng Z, Ma X, Hu Y, Li J, Bryant D. A Simulation Study to Improve Quality of Care in the Emergency Department of a Community Hospital. Journal of Emergency Nursing 2012;38(4):322–8. doi:10.1016/j.jen.2011.03.005.

- A review of the application of simulation techniques to evaluate emergency department operations is provided
- A comprehensive classification based on KPIs, improvement options and their relation is presented
- The review shows the importance of investigating combinations of KPIs and improvement options
- The analysis of relations between KPIs and improvement options provides insights into which options have an effect on which KPIs
- Relevant, unexplored and promising areas for future research are revealed