9-2016

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Published in *Operations Research for Health Care*, September 2016, Volume 10, Pages 13–22

http://doi.org/10.1016/j.orhc.2016.05.001

Abstract

Long waiting times in emergency departments (EDs) not only reduce patients' perceived quality of care, but also increase crowding which can adversely affect patients' outcomes. Waiting time has been found to affect patients' outcomes and is closely associated with delays in the provision of ancillary services to ED patients by the diagnostic/treatment laboratories. The focus of this study is to improve the flow of ED patients by testing alternative triage processes and capacity of physicians, triage nurses and laboratories. Three alternative triage processes are examined for managing the flow of ED patients through shared and dedicated laboratories across different utilization of physicians, triage nurses, and laboratories using a discrete event simulation (DES) model that captures the pertinent characteristics of EDs operating in tertiary acute care hospitals under conservative assumptions. Our results show that choosing the appropriate triage process and adding extra capacity to the triage and dedicated laboratory can significantly improve ED performance, especially when physician utilization is high. In contrast, adding extra capacity to a shared laboratory improves performance only slightly. Our results also show that shared laboratory generally provides better support to EDs than dedicated laboratory.

Keywords: Emergency department; Triaging; Healthcare quality improvement; Simulation

1. Introduction

The emergency department (ED) is often the starting point for patient flow through a hospital for unscheduled urgent care, and it is a critical bottleneck [1]. Crowding, long waiting times, and queues are well-known problems in many EDs globally [2] and [3]. Long waiting times not only reduce patients' perceived quality of care, but also increase crowding which can adversely affect patients' outcomes [4]. As crowding is a perennial issue in most EDs, there is a constant need to reduce crowding and its adverse effects on patients' outcomes. To improve efficiency and patients' outcomes in EDs, a variety of interventions has been proposed. The effects of enhancements to physical infrastructures, such as computerized physician order entry (CPOE) system [5], ED admission unit [6], RFID [7], and short-stay wards [8], have been reported in the literature. A range of causes for ED crowding has also been postulated, including hospital bed shortages, variable medical acuity of patients, patient volumes, and shortage of space, equipment and staff [9] and [10].

Asplin et al. [11] proposed a conceptual model that divides ED functions into input, throughput and output stages to identify issues and opportunities to alleviate ED crowding. Throughput factors related to processes and efficiencies in EDs, such as staffing schedules, layout designs, and efficiencies of its ancillary processes (e.g., diagnostic and treatment laboratories), are cited to affect the ability of EDs to achieve a smooth flow of patients. The focus of our study is to improve the throughput factors in EDs by examining the front-end triage processes, and the sharing and balancing of resources, such as physicians, triage nurses, and supporting laboratories, associated with the treatments of ED patients.

Three key performance measures are used in this study to assess ED performance. The first measure is the mean patient cycle time, which is more commonly known as ED length of stay (EDLOS) [12] and [13]. EDLOS can be defined as the mean time between a patient's arrival and discharge, or if admitted into the hospital, the point when the patient leaves the ED [14]. The second measure is the variability of patients' length of stays (VLOS) in the ED, which is measured as the standard deviation of EDLOS. The third measure is the mean time between a patient's arrival and start of his or her first consultation with a physician, commonly labeled as the time to first consultation (TFC). These three performance measures have been found to affect patients' outcomes, such as inpatient length of stay and hospital mortality for a variety of time-sensitive medical conditions, even after adjusting for patients' characteristics and comorbidities [15], [16] and [17]. In addition, EDLOS has a direct impact on ED crowding which not only affects patients' outcomes [4] and [9], but also reduces staff productivity and patient satisfaction [18]. Past research has also reported a close relation between EDLOS and waiting times for laboratory results, such as blood tests, X-rays and CT scans, from diagnostic laboratories [10] and [14]. Patients who require laboratory services suffer not only longer waits but also higher risks of negative patients' outcomes due to long waiting times for test results and delayed treatments. It is thus important to improve the EDLOS, VLOS, and TFC of ED patients, especially patients who require laboratory services.

The effective allocation of resources across an entire ED workflow is a key to achieving a smooth and efficient ED process, and improvements of the front-end triage processes and laboratory services offer opportunities to improve the ED workflow. Our study thus provides useful insights to improve the performance of EDs using a discrete event simulation (DES) model to examine alternative triage processes to channel patients through the shared and dedicated laboratories under different utilization levels of physicians, triage nurses, and laboratories.

The contribution of our study is to provide managerial insights on not only the main effects of alternative triage processes, shared versus dedicated laboratory, physician utilization, and extra triage and laboratory capacity, but also their interactions to improve the performance of EDs. The rest of this paper is organized as follows: Section 2 begins with a literature review of triage processes, shared versus dedicated laboratories, and discrete event simulation for modeling EDs. Section 3 describes the simulation model of an ED built in this study to compare the alternative triage processes with shared and dedicated laboratories. Section 4 proposes a simulation experiment designed to analyze the impact of four factors, namely the alternative triage processes and different utilization of physicians, triage nurses and laboratories, which affect the EDLOS, VLOS and TFC of ED patients who may or may not require services from the shared vis-à-vis dedicated laboratories. Section 5 presents the results of the simulation, and Section 6 discusses the managerial insights. Section 7 concludes with a summary of our findings and proposes some areas for future research.

2. Literature review

2.1. Triage processes in EDs

Triage essentially refers to the classification of ED patients for treatment in situations of scarce resources according to the patients' medical conditions and an established sorting plan [19]. Various ED triage classification procedures have been reported in the literature, including the algorithmic Manchester Triage Scale (MTS) [20], the 5 levels Emergency Severity Index [20] and the Canadian Triage and Acuity Scale

[21] and [22]. A common feature of these procedures is to sort incoming patients into 3 to 5 different groups. As an example, the classification procedure used in many EDs in Singapore is a symptom based approach to sort patients into 4 broad groups based on the national Patient Acuity Category Scale (PACS): (1) PAC1 patients are the most serious, time-critical patients who require immediate attention or resuscitation; (2) PAC2 patients are non-ambulant patients who appear to be in a stable state with no immediate danger of collapse; (3) PAC3 refers to ambulant patients, and; (4) PAC4 are non-emergency patients [23]. As this study is concerned with emergency patients, the focus is on the PAC1, PAC2 and PAC3 patients. For ease of exposition, these patients will be referred to as P1, P2 and P3 patients respectively.

An initial triage is often recommended and used to sieve out the P1 and more critical P2 patients for immediate attention before a formal triage. If resuscitation is required, the patient is admitted directly into the resuscitation area; otherwise, the patient is directed to either a critical care area or a waiting area depending on the patient's conditions. The initial triage is used to identify the P1 and more critical P2 patients as one group for direct admissions into the resuscitation or critical care area, whereas the other group of less critical P2 and non-urgent P3 is directed to a waiting area and treated through a separate process. While the treatments of both patient groups are worthy of analysis, the focus of this study is on the latter patient group which goes through a relatively universal treatment pathway consisting of formal triages, consultations, laboratory services, and patient dispositions.

Many methods have been proposed in the literature to improve the triage processes. A list of different methods is described by Wiler et al. [24]. Some of the well-documented triage methods include immediate bedding [24], bedside registration [13] and [25], fast-tracking/fast-track lane [26], [27] and [28], advanced triage protocols [29], [30], [31], [32] and [33], and deployment of physicians at triage [34], [35] and [36]. Immediate bedding and bedside registration have been described in the literature as the simultaneous implementation of bedding and simple registration of patient's information capturing only basic demographics information. The objective is to bed acute patients, such as the P1 and more critical P2 patients, quickly with minimal delays. Fast-tracking/fast-track lane is another method which involves providing a separate and less urgent care area for low acuity patients who can be treated simply and quickly [26], [27] and [28]. The idea is similar to the use of the Short Processing Time dispatching rule in job shops to process small jobs first, which, in turn, reduces the average number of jobs and crowding in job-shops [37], [38] and [39]. Obviously, extra resources must be deployed to operate a fast-track lane. Otherwise, the improvement in flow times of fast-tracked patients is at the expense of longer waits for other ED patients.

Another popular method is the use of advanced triage protocols (ATPs) which typically involve the identification of certain illness conditions and implementation of standardized treatment pathways, such as a specific diagnostic, therapeutic, and/or pain management plan based on the patient's complaints or triage physician's assessment [34], [35] and [36]. ATPs are often implemented with the deployment of physicians at triage. They may also be implemented via the deployment of better-trained advanced triage nurses (ATNs) instead of physicians, or via a team-based triage approach which deploys triage teams comprising of an emergency physician, nurse, registrar, technician and/or scribe to initiate comprehensive medical evaluations upon patients' entries into EDs [34]. Various ATPs have been proposed for certain illnesses complete with treatment plans. Some of these protocols include the administration of medication for pain management [30], initiation of chest radiograph (CXR) for chest injuries and suspected pneumonia [33], and rapid electrocardiogram (ECG) for acute myocardial infarction [29].

Increasingly, ATPs are implemented with advanced triage nurses trained and empowered to initiate such protocols. In particular, recent studies have concluded that the prescriptions of diagnostic tests and treatments to ED patients are closely associated with extended EDLOS [14]. One solution in this respect is to streamline the flow of such patients by implementing ATPs within a triage process. While ATPs have been cited to improve the time to first consultation and employee satisfaction in certain implementations [40], no past study has systematically examined the use of ATPs within a triage process to route patients (who may or may not require laboratory services) differently through EDs with different staffing levels of physicians, triage nurses and laboratory resources. Since patients who require laboratory services are often more acute than those who do not require laboratory services, it is important the acute patients are treated promptly. Our objective in this paper is to test the efficacy of three alternative triage processes to route patients who may or may not require laboratory services, and to identify situations, if any, where the benefits of these triage processes are amplified or muted. The three alternative triage processes are proposed and described in Section 4.1.

2.2. Shared versus dedicated laboratories in EDs

Laboratories in a hospital include not only diagnostic facilities, such as blood-test, X-ray, and CT-scan, but also treatment facilities, such as wound dressing. These laboratories can be set up as either a dedicated or shared facility. A dedicated laboratory, such as a diagnostic imaging machine, may be set up within, or close to, an ED to serve ED patients only. In contrast, a shared laboratory is often sited in a more centralized location to provide laboratory services to different medical departments in a hospital. For example, an ED may send blood specimens through high pressure pneumatic tubes to a shared laboratory, and the test results are then relayed back electronically to the ED. In most modern hospitals, the logistical infrastructures linking remote facilities together are fairly well-developed; and delays linking an ED with shared laboratories are often minimal [41].

Shared laboratories have been used traditionally in hospitals and healthcare institutions for the benefit of cost efficiencies and economy of scale. The rapid development of laboratory automation for consolidated testing has also further enhanced the efficacious use of resources in shared laboratories. Nevertheless, the use of satellite laboratory is an alternative that remains common in emergency care. These laboratories are usually situated within or near to an ED, and have dedicated laboratory equipment, supplies and manpower to serve ED patients only. Rapid technological advancements have also accelerated the development and adoption of micro-technology to deliver laboratory testing services in a near patient setting, commonly known as point-of-care test (POCT) [42]. However, the advancement of POCT has yet to fully replace the needs for shared and dedicated laboratories.

In many tertiary hospitals, demands for laboratory services are typically pooled to serve different parties, such as ED, specialist outpatient clinics, and inpatient wards, although priority is given to ED requests. While the pooling of laboratory services is known to have a positive impact on the overall performance of a hospital, its impact is not totally obvious for an ED that shares the centralized laboratory with other departments. This study thus includes the examination of centralized (or shared) versus decentralized (or dedicated) laboratories on the treatments of ED patients.

2.3. Discrete event simulation of EDs

Discrete event simulation (DES) has been used widely to study and improve ED operations in healthcare systems across the entire input–throughput–output stages to alleviate crowding based on a variety of performance indicators [43], [44], [45], [46] and [47]. Experimental results using simulation models have shown that the acceptance of non-critical patients, priority rule for serving patients, and number of physicians affect the performance of EDs [45]. The value of fast-tracking systems, where dedicated facilities are available for treating patients with minor injuries during peak times, has also been studied [48]. Strategic, tactical and operational issues related to the ED throughput stages, ranging from staff scheduling [45] to comparative studies of competing ED operational designs [46], have also been addressed using DES models. A handful of studies use the perspective of queuing theory [49] and [50]. Other studies use DES in the context of "lean management" to achieve a smoother patient flow through the EDs by eliminating wastes in the form of inventory, delays, transportation, and inappropriate orders [50] and [51]. DES is thus an appropriate tool for modeling and studying the operations of EDs. To the best of our knowledge, this research is the first to study alternative triage processes, shared versus dedicated laboratories, and balancing of physician, triage and laboratory resources simultaneously in a single study.

3. Simulation model

A simulation model of a generic ED was built using the simulation software ARENA [52]. Our objective is to generate generic insights on improving the performance of EDs; and this warrants a simulation model that represents broadly the variety of EDs in practice rather than a specific ED [53]. The past literature on EDs provides characteristics of the work flows in typical EDs [54], [55] and [56]. The pertinent processes and decisions involved in the flow of ED patients are shown in Fig. 1. While the pathways of individual patients through an ED may differ based on the decisions made within an ED, most patients will go through the unshaded processes, such as triage and consultation, with a small minority routed to the shaded processes, such as extended ED observation or other discipline review. To realistically limit the scope of our study, our model is focused on the major pathways, which involve the unshaded processes such as triage, first consultation, laboratories that provide the diagnostic tests, treatments, or observations, follow-up consultation, and patient disposition as shown in Fig. 1. Most of these work steps are sequential with some possible iterative progressions between intermediate steps, such as laboratory services and consultations with physicians.

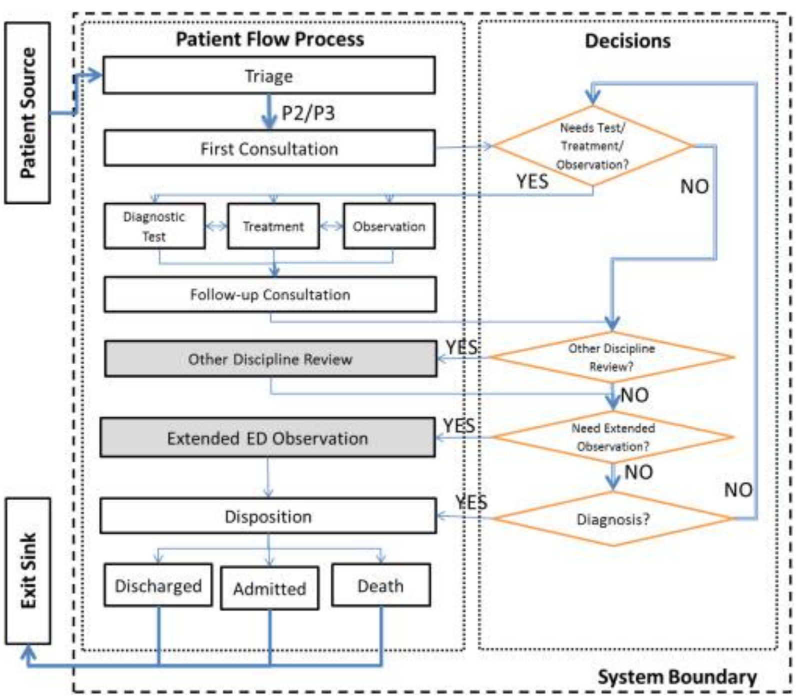

Fig. 1. Typical processes and decisions in EDs.

While there are many past simulation studies and models on EDs, most are focused on modeling a specific ED. Their findings are thus precise, but specific to a single ED, and are not readily generalizable to other EDs. To provide insights that remain true across different EDs, the challenge is to build a generic ED model. Fortunately, as EDs and job shops are known to operate in the same way, we can refer to the large body of literature on job-shop simulation for guidance on building a generic ED model [37], [38] and [39]. The literature on job-shop simulation shows that certain factors, such as shop size, proportion of jobs with different routings, and pattern of job arrival and processing times, do not affect the relative effectiveness of policies such as the scheduling and dispatching rules in job-shops. Consequently, ED size, proportion of patient types, and pattern of patient arrival and service times are not expected to affect the pattern of our results and these factors can be fixed. Our baseline simulation model can thus be represented as an ED with 4 physicians and 2 triage nurses, supported by a dedicated laboratory within the ED and a shared laboratory in another part of the hospital. Based on our experience with EDs in Singapore and overseas, this model represents a medium-size ED capable of handling 128 patients per shift, i.e. 4 physicians serving 4 patients per physician per hour on an 8-hour shift. Arriving patients are first attended by triage nurses, and service times are assumed to be lognormal with a mean of 6 min and a standard deviation of 3.45 min. The consultation times with a physician are also assumed to be lognormal with a mean of 12 min and a standard deviation of 6.9 min. For patients who require laboratory services, the diagnostic tests or treatments are assumed in the midst of consultations such that their consultations are split into two equal time segments to consult the same physician twice. Laboratory service times are assumed to be lognormal with a mean of 20 min and a standard deviation of 7 min. These assumptions on the service times are similar to those used by Salzarulo et al. [56] in their generic simulation model of a real clinic.

In the baseline simulation model, 30% of all arriving patients require laboratory services, and these requests are sent to either a dedicated or shared laboratory with equal probability. The dedicated laboratory is modeled as a single server system, and serves only ED patients. In contrast, the shared laboratory is modeled with two servers, and receives 50% of its requests from the ED and the other 50% from the rest of hospital with a higher service priority given to ED requests. Theoretically, it is well known that the benefit of pooling increases with more servers and a smaller percentage of higher priority jobs in the pooled facility. Consequently, our simulation model has taken a conservative stance to avoid overstating the value of laboratory sharing/pooling by modeling only two servers and ED contributing a large 50% of all jobs in the shared laboratory. The mean arrival rate of patients into the ED and the request rate for laboratory services from the rest of the hospital into the shared laboratory are adjusted such that the mean utilization of the physicians, triage nurses and laboratories equal 75% in the baseline model. To compare the EDLOS, VLOS and TFC of patient groups who may or may not require services from the shared or dedicated laboratory, the performance measures for three patient groups are collected: (1) “NL” patients who do not require any laboratory services; (2) “SL” patients who require services from the shared laboratory; and (3) “DL” patients who require services from the dedicated ED laboratory.

Finally, to further ensure that the fixed factors do not affect the pattern of our results, pilot simulation runs with different ED size, proportion of patient types, and pattern of patient arrival and service times are tested. Consistent with the literature on job shop simulation, our pilot simulation runs indicate that the fixed factors in our simulation model do not affect the pattern of our results on the alternative triage processes and experimental factors tested in our paper. In other words, our results on the triage processes and experimental factors are valid and generalizable across EDs with different ED size, proportion of patient types, and pattern of patient arrival and service times.

4. Experimental design

The following experiment is designed to evaluate the effects of four factors that affect the EDLOS, VLOS and TFC of different patient groups, namely: (1) alternative triage processes; (2) physician utilization; (3) extra triage capacity; and (4) extra laboratory capacity.

4.1. Alternative triage processes

Three alternative triage processes labeled as T1, T2 and T3 are considered in this study. Fig. 2 shows the process flowcharts for the three alternative processes. These triage processes are used for the less critical P2 and non-urgent P3 patients.

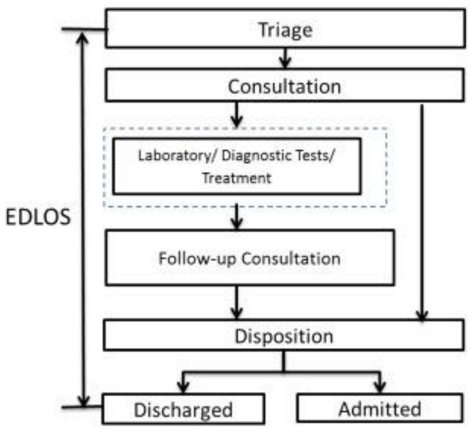

Fig. 2(a). (a) T1 triage process.

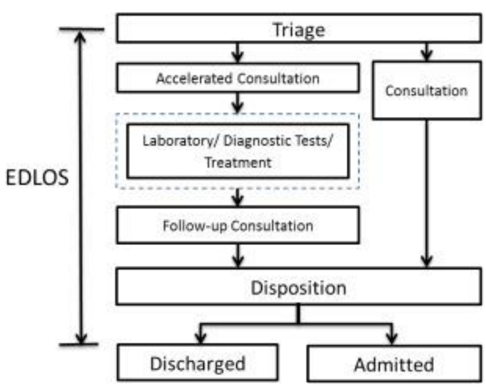

Fig. 2(b). (b) T2 triage process.

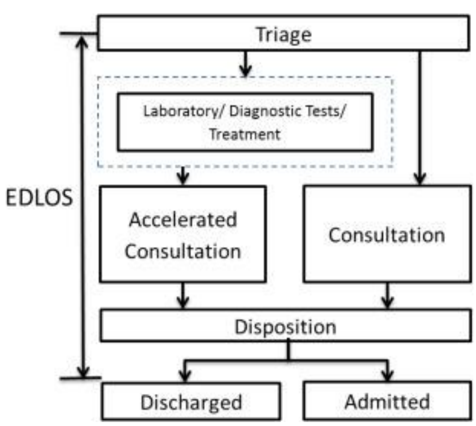

Fig. 2(c). (c) T3 triage process.

Fig. 2 Patient flow in EDs under different triage processes: (a) T1 triage process; (b) T2 triage process, and; (c) T3 triage process.

In T1, triage nurses serve all arriving patients on a first come first served (FCFS) basis by collecting vital signs and statistics of each patient. The patients are then directed to a waiting area and are seen by physicians on a FCFS basis. This is the typical triage process of many existing EDs. Patients who require laboratory services are diverted to a laboratory only after their first consultations with a physician. These patients will then return to the waiting area. When the laboratory result is ready, the patient will be called for a second consultation with the same physician. The priority of the physicians is to serve patients waiting for their second consultations in order to minimize the EDLOS of patients who require laboratory services. All patients waiting for their first consultations are served on a FCFS basis and are not differentiated by whether they require laboratory services or not.

In T2, triage nurses also see arriving patients on a FCFS basis, but classify them after triage into two groups—those who require laboratory services and those who do not. Patients who require laboratory services are given higher priority by the triage nurses to see a physician before those who do not require laboratory services. After the first consultation with a physician, a patient who requires laboratory services is sent to the laboratory before returning to the waiting area. When the laboratory result is ready, the patient will be called for a second consultation with the same physician. Patients waiting for second consultations are given higher priority over patients waiting for first consultations. The triage nurses in T2 are trained to identify patients who require laboratory services during triage and to assign these patients higher priority to see the physicians who can then order the required laboratory services earlier.

In T3, triage nurses see arriving patients on a FCFS basis but these nurses are trained to order the appropriate laboratory services for patients on behalf of physicians. An alternative implementation is to deploy a physician at the triage area who can order the required laboratory services. Such patients are first sent to the laboratory before they are sent to the waiting area. The priority of the physicians is to serve patients who have received their laboratory results over other patients waiting for their first consultations. In T3, patients who require laboratory services see a physician only once after their laboratory results are ready. In contrast, patients who require laboratory services under T1 and T2 triage processes consult the physicians twice (before and after the laboratory results).

In summary, triage nurses in T1 require the lowest level of training and competence while nurses in T3 require the highest level of competence. In T1 and T2, all patients wait for initial consultations with the physicians after triage. T2 represents a triage process whereby patients with selected presentations that require laboratory tests, will be prioritized for an initial consultation with a physician who can then order the laboratory services earlier. In T3, patients requiring laboratory services are diverted immediately to these laboratories (potentially via ATPs), so that the laboratory results are available before consultations with the physicians.

4.2. Physician utilization

Although the literature on job-shop simulation shows that the proportion of job types, arrival rates, and processing times do not affect the relative effectiveness of policies in different job-shops, their combined effect with respect to utilization does matter. When utilization is low, there are few waiting jobs for the priority rules to differentiate or process differently. As utilization increases, there are more waiting jobs and the relative effectiveness of the priority rules becomes more distinct.

As the supply of well-trained ED physicians is limited and costly, physician utilization in EDs is rarely less than 75% but rather closer to 100%. Two levels of physician utilization are thus examined in this study. The mean patient arrival rates are set at two levels corresponding to a low and high physician utilization of 75% and 95%. A high level of physician utilization will obviously increase the waiting times of all patients. But its main effect and interactions with the other factors, such as the triage policies, and extra triage and laboratory capacity, on the ED performance are less obvious.

4.3. Extra triage and laboratory capacity

The cost of triage nurses and laboratory services is often lower than the cost of physicians. The provision of extra triage and laboratory capacity is thus an option to better support and smooth the flow of ED patients through the physicians. While the capacity of physicians is often an unavoidable bottleneck, the provision of extra supporting resources, i.e. triage nurses and laboratories, is often viewed as a possible and more cost-effective option to improve ED performance relative to expanding the capacity of physicians. The impact of extra triage and laboratory capacity are examined by increasing the number of triage nurses and by reducing the demands for laboratory services, respectively.

The proposed simulation experiment evaluates two levels of physician utilization of 75% (low) and 95% (high). With two triage nurses, the mean utilization of the triage nurses also corresponds to 75% and 95% at low and high physician utilization respectively. At these factor settings, both the physicians and triage nurses are bottlenecks and no extra triage capacity is provided to break the bottlenecks. To investigate the impact of extra triage capacity, the number of triage nurses is increased from 2 to 3 nurses—an increase of 50%. With the extra triage capacity, the mean utilization of the triage nurses reduces to 50% and 63.3% at low and high physician utilization respectively such that triage is no longer a bottleneck. The expected utilization of the triage nurses at low and high physician utilization with 2 and 3 nurses is summarized in Table 1. This is equivalent to providing no extra or extra triage capacity to support the physicians as bottlenecks.

Table 1.

Mean utilization of supporting resources at 75% and 95% physician utilization.

Number of triage nurses	Utilization of triage nurses	
	75% physician utilization	95% physician utilization
2	75.0%	95.0%
3	50.0%	63.3%
Percentage of patients who require laboratory services	Utilization of laboratory	
	75% physician utilization	95% physician utilization
30%	75.0%	95.0%
20%	50.0%	63.3%

Similarly, the provision of extra laboratory capacity is examined at two levels—no extra and extra. In the base-case, the percentage of ED patients who require laboratory services equals to 30% of all arriving patients. At this setting of 30%, the mean utilization of the laboratories equates to 75% and 95% at low and high physician utilization, such that both physicians and laboratories are bottlenecks, i.e. no extra laboratory capacity is provided. By reducing the percentage of requests for laboratory services to 20%, an extra laboratory capacity of 50% is effectively added such that the mean utilization of the laboratories reduces to 50% and 63.3% at low and high physician utilization as shown in Table 1.

In summary, the proposed simulation experiment involves running the simulation model for 24 combinations of factor levels. These include the 3 triage processes, 2 levels of physician utilization, 2 levels of extra triage capacity, and 2 levels of extra laboratory capacity as summarized in Table 2. In each simulation run, the batch mean method was used to collect 30 observations of EDLOS, VLOS and TFC for each of the three patient groups. To eliminate the initial transience, each simulation was run for 4000 h before 30 observations were collected on batch lengths of 4000 h each. The advantage of the full factorial design permits a complete analysis of how each factor should be managed relative to the other factor settings.

Table 2. Experimental factors.

Factors	Levels
Triage processes	T1, T2 & T3
Physician utilization	75% & 95%
Extra triage capacity	Nil & Extra
Extra laboratory capacity	Nil & Extra

5. Results

The simulation results focus on EDLOS, VLOS and TFC as three performance measures to evaluate the trends of improvements related to the three postulated triage processes, shared versus dedicated laboratory, capacity of physicians (based on physician utilization), and extra triage and laboratory capacity (based on whether extra capacity is deployed). The pattern of the results for EDLOS and VLOS is the same. The EDLOS and VLOS of each patient group (i.e. NL, SL, and DL) are therefore tabulated together in Table 3(a), (b), and (c), respectively. The highest-order and statistically significant interactions are the two-way interactions between physician utilization and the other three experimental factors. These three interactions on the EDLOS for each patient group are plotted in Fig. 3(a), (b) and (c).

Table 3. EDLOS and VLOS of different patient groups under different scenarios (hours).

Physician utilization		75%		95%	
Extra triage capacity		Nil	Extra	Nil	Extra
(a) NL patients					
T1	Lab—Nil	0.4303a	0.3692	1.3139	0.8891
		0.2026b	0.1705	0.8730	0.6646
	Lab—Extra	0.4321	0.3720	1.3177	0.8996
		0.2035	0.1720	0.8751	0.6720
T2	Lab—Nil	0.4380	0.3798	1.4390	1.0652
		0.2136	0.1871	1.0024	0.8881
	Lab—Extra	0.4373	0.3795	1.4028	1.0231

Physician utilization		75%		95%	
Extra triage capacity		Nil	Extra	Nil	Extra
		0.2106	0.1836	0.9578	0.8248
T3	Lab—Nil	0.4513	0.3886	1.5020	1.0684
		0.2222	0.1936	1.0331	0.8664
	Lab—Extra	0.4468	0.3860	1.4298	1.0372
		0.2163	0.1883	0.9647	0.8286
(b) SL patients					
T1	Lab—Nil	0.9589	0.8985	1.9474	1.5253
		0.2965	0.2729	0.9086	0.7084
	Lab—Extra	0.9053	0.8460	1.8468	1.4286
		0.2823	0.2590	0.8998	0.7026
T2	Lab—Nil	0.9332	0.8636	1.5829	1.0053
		0.2820	0.2515	0.7099	0.2748
	Lab—Extra	0.8791	0.8082	1.4790	0.8989
		0.2657	0.2337	0.6996	0.2484
T3	Lab—Nil	0.8408	0.7703	1.4595	0.8782
		0.2546	0.2239	0.7011	0.2468
	Lab—Extra	0.7836	0.7105	1.3546	0.7722
		0.2359	0.2024	0.6882	0.2181
(c) DL patients					
T1	Lab—Nil	1.4135	1.3515	5.8446	5.3465
		0.7418	0.7223	4.6253	4.8247
	Lab—Extra	1.0436	0.9848	2.0922	1.6794
		0.3967	0.3803	0.9968	0.8235
T2	Lab—Nil	1.3902	1.3218	5.0041	4.5462
		0.7343	0.7378	3.6410	3.8338
	Lab—Extra	1.0153	0.9465	1.7154	1.1436
		0.3880	0.3675	0.8157	0.4913
T3	Lab—Nil	1.2930	1.2224	4.8251	4.2655
		0.7258	0.6951	3.9681	3.5942
	Lab—Extra	0.9231	0.8523	1.5901	1.0171
		0.3702	0.3488	0.8111	0.4775

a EDLOS.

b VLOS.

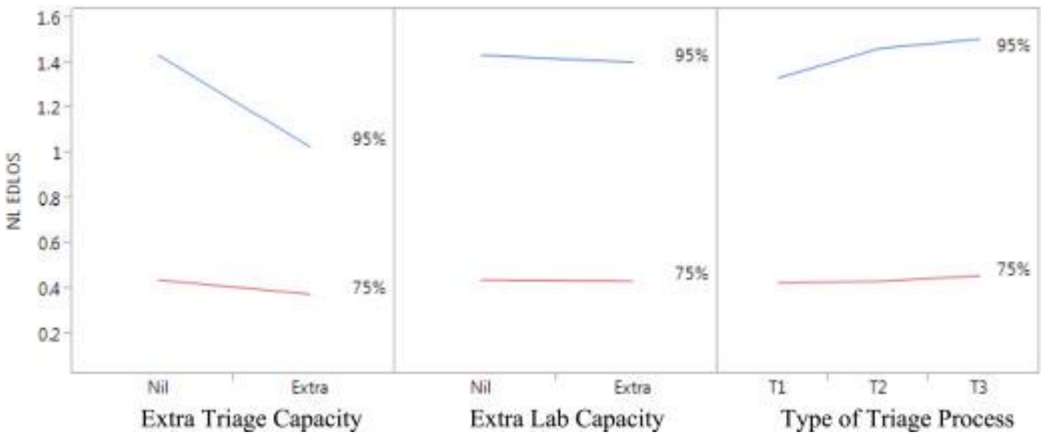

Fig. 3(a). (a) EDLOS of non-laboratory (NL) patients.

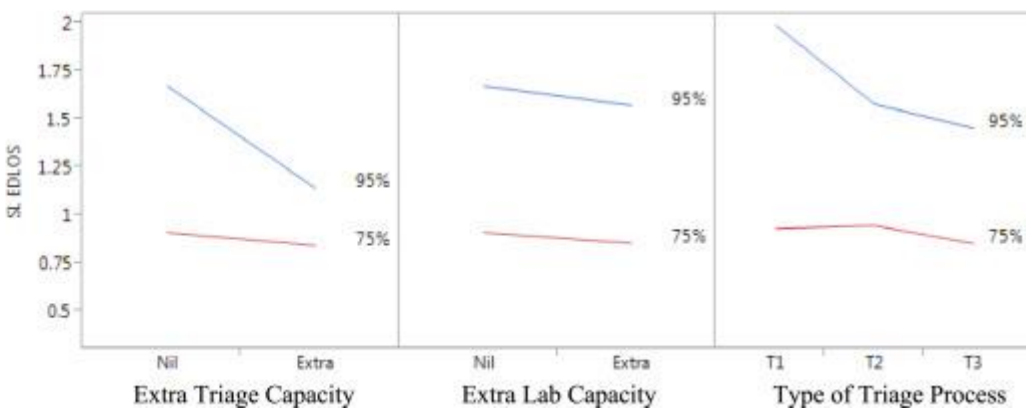

Fig. 3(b). (b) EDLOS of shared laboratory (SL) patients.

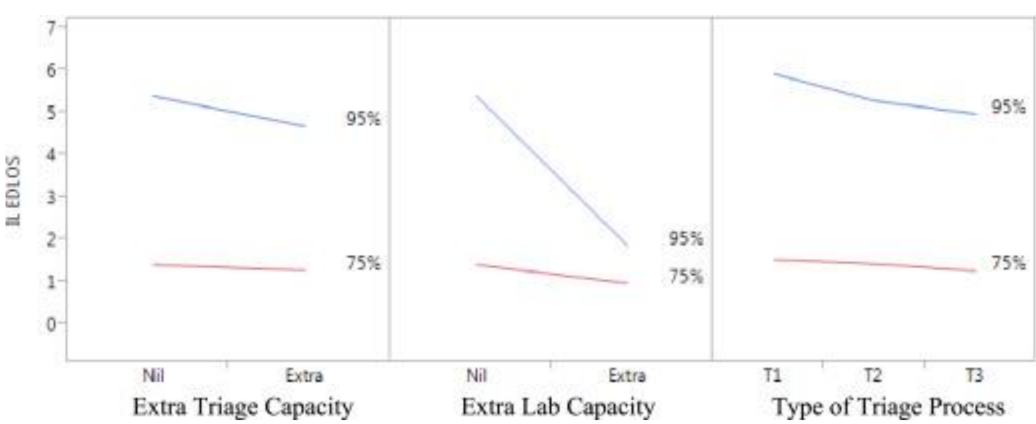

Fig. 3(c). (c) EDLOS of dedicated laboratory (DL) patients.

Fig. 3 Interaction plots for EDLOS at low and high physician utilization.

Fig. 3(a) shows the two-factor interactions of EDLOS for NL patients who do not require laboratory services, and the effects of each experimental factor under different levels of physician utilization. At low physician utilization, the EDLOS of NL patients is only slightly affected by the triage process, extra triage capacity and extra laboratory capacity. At high physician utilization, the EDLOS of NL patients is significantly larger, suggesting that physician utilization has the largest impact on the EDLOS of NL patients relative to the other factors. Three interesting effects are noted in the subplots in Fig. 3(a): (i) the provision of extra triage capacity reduces the EDLOS of NL patients slightly at low physician utilization, but significantly at high physician utilization; (ii) at both low and high physician utilization, the provision of extra laboratory capacity has little or no impact on the EDLOS of NL patients as these patients do not require laboratory services; and (iii) the EDLOS of NL patients in T3 triage process is the largest followed by T2 and T1 triage process; but the difference is relatively small even at high physician utilization.

Setting a low physician utilization target has the largest positive impact on the EDLOS of NL patients, followed by the provision of extra triage capacity. Choosing a triage process, such as T2 or T3, which gives priority to patients who require laboratory services increases the EDLOS of NL patients only marginally as long as the percentage of such patients is within the range of 20%–30% modeled in our simulation. To reduce the EDLOS of NL patients, a manager can either increase the capacity of physicians or provide extra triage capacity.

Fig. 3(b) shows the two-factor interactions of EDLOS for SL patients who require services from the shared laboratory. Some interesting effects are shown in the subplots in Fig. 3(b): (i) the provision of extra triage capacity reduces the EDLOS of SL patients slightly at low physician utilization, but more significantly at high physician utilization; (ii) the provision of extra laboratory capacity reduces the EDLOS of SL patients only slightly by similar margins at both low and high physician utilization; and (iii) the triage process T3 performs better than T2, and both perform significantly better than T1 especially at high physician utilization with significantly smaller EDLOS for SL patients. This figure shows that physician utilization has the largest impact on the EDLOS of SL patients, followed by the triage process, extra triage capacity, and extra laboratory capacity. It may be a surprise, at least initially, that the provision of extra laboratory capacity has the smallest impact on reducing the EDLOS of SL patients. Nevertheless, as SL patients are always given higher service priority in the shared laboratory, it is understandable that the provision of extra capacity in the shared laboratory is more important and beneficial for requests from other departments rather than for SL patients. When the triage process T3 and extra triage capacity are implemented together to advance ED requests into the shared laboratory, the shared laboratory is still, interestingly, able to handle the ED requests fairly promptly with or without extra laboratory capacity (see Table 3(b)).

Fig. 3(c) shows the two-factor interactions of EDLOS for DL patients who require services from the dedicated laboratory. The subplots in Fig. 3(c) again reveal interesting effects among the experimental factors, summarized as follows: (i) the provision of extra triage capacity reduces the EDLOS of DL patients slightly at low physician utilization, but significantly at high physician utilization; (ii) the provision of extra laboratory capacity reduces the EDLOS of DL patients significantly at low physician utilization and even more significantly at high physician utilization; and (iii) the triage process T3 performs better than T2, and both perform better than T1 especially at high physician utilization with significantly smaller EDLOS. The figure, again, shows that physician utilization has the largest impact on the EDLOS of DL patients, followed by extra laboratory capacity, triage process, and extra triage capacity. Relative to the other factors, both the triage process and extra triage capacity have the smallest impact on the EDLOS of DL patients. As most dedicated laboratories operate frequently with limited number of servers, expediting DL patients into a dedicated laboratory (through a triage process or extra triage capacity) will only increase waiting in the dedicated laboratory, with limited improvement in EDLOS of DL patients.

A basic premise of a good triage process is to balance the EDLOS of different patient groups. It is thus important to compare the impact of the triage processes on the EDLOS of different patient groups simultaneously. To facilitate the comparison, Fig. 4 plots the EDLOS of NL, SL, DL patients across the 3 different triage processes at low and high physician utilization. Since the triage processes T2 and T3 give SL and DL patients higher service priority relative to NL patients, T2 and T3, intuitively, reduce the EDLOS of SL and DL patients but increase the EDLOS of NL patients relative to T1. Fig. 4 shows that both T2 and T3 reduce the EDLOS of SL and DL patients significantly. Relative to T1, T3 offers the largest mean improvement in EDLOS for SL and DL patients of 14% and 11%, respectively, at low physician utilization. The improvement for the two patient groups increases to 34% and 22% at high physician utilization. At the same time, relative to T1, T3 increases the EDLOS of NL patients moderately by 4% and 14% at low and high physician utilization. These findings suggest the potential of significant reduction in EDLOS with the deployment of accelerated consultation for patients who require laboratory services, with the effects most obvious in congested EDs with high physician utilization.

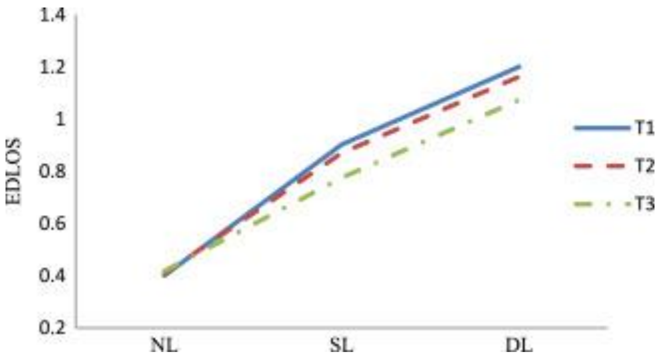

Fig. 4(a). (a) 75% physician utilization.

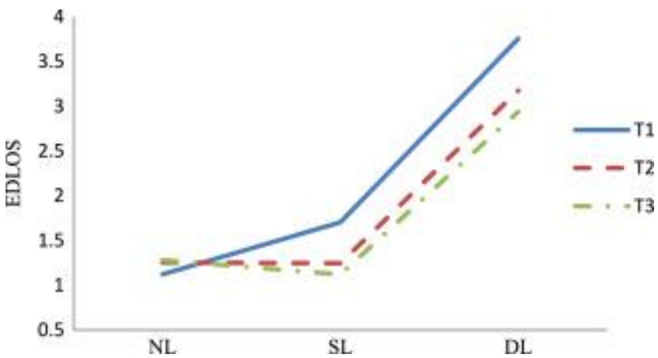

Fig. 4(b). (b) 95% physician utilization.

Fig. 4 EDLOS of NL, SL, DL patients with different triage processes and physician utilization.

Fig. 4 also shows that the EDLOS of SL patients is much shorter than that of DL patients at both low and high physician utilization. Intuitively, a shared laboratory offers significant advantages. Both Fig. 4(a) and 4(b) show that the EDLOS of SL patients is significantly smaller than that of DL patients across all triage processes, with an average improvement of 26% (59%) at low (high) physician utilization. Consequently, the pooling of laboratory resources together into a single location offers significant advantage, especially in periods of high utilization, unless travel times to the laboratory negate the advantage totally. The use of rapid transportation technology, such as high pressured pneumatic tubes, to transport specimens will ensure that such delays are kept to a minimum. While it may be good to have a dedicated laboratory within an ED for the most acute and immobile patients, our results suggest that such laboratory should be used strictly for that purpose.

As noted above, the results for EDLOS and VLOS in Table 3 vary in the same pattern with the experimental factors. The above discussion on EDLOS therefore also applies to VLOS. The results on TFC of the 3 patient groups (i.e. NL, SL, and DL) are tabulated in Table 4(a), (b), and (c). The effects of the experimental factors on TFC are within expectation. Extra triage capacity reduces the TFC of all patients significantly, especially at high physician utilization. Extra laboratory capacity, however, has no or minimal effects on the TFCs of T1 and T2 as both triage processes send patients to the laboratories only after their first consultations with physicians. In contrast, T3 sends patients directly to the laboratories before their first consultations with physicians. Consequently, adding extra laboratory capacity in T3 can potentially reduce the TFC of patients who require the laboratory results before their first consultations with physicians. Specifically, Table 4(b) and (c) shows that the TFCs of SL (DL) patients reduce marginally (significantly) when extra laboratory capacity is added in triage process T3. This observation is consistent with our earlier observation that extra laboratory capacity improves the flow time through a shared (dedicated) laboratory marginally (significantly). It is also noted that while T3 offers patients who require laboratory services the smallest EDLOS and VLOS, it also yields the largest TFC for all patients relative to the other two triage processes.

Table 4. TFC of different patient groups under different scenarios (hours).

Physician utilization		75%		95%	
Extra triage capacity		Nil	Extra	Nil	Extra
(a) NL patients					
T1	Lab—Nil	0.2303	0.1692	1.1139	0.6891
	Lab—Extra	0.2321	0.1720	1.1177	0.6996
T2	Lab—Nil	0.2380	0.1798	1.2390	0.8652
	Lab—Extra	0.2373	0.1795	1.2028	0.8231
T3	Lab—Nil	0.2513	0.1886	1.3020	0.8684
	Lab—Extra	0.2468	0.1860	1.2298	0.8372
(b) SL patients					
T1	Lab—Nil	0.2304	0.1689	1.1137	0.6891
	Lab—Extra	0.2320	0.1717	1.1166	0.6979
T2	Lab—Nil	0.2051	0.1328	0.7558	0.1702
	Lab—Extra	0.2051	0.1321	0.7522	0.1669
T3	Lab—Nil	0.6407	0.5704	1.2595	0.6781
	Lab—Extra	0.5837	0.5108	1.1542	0.5724
(c) DL patients					
T1	Lab—Nil	0.2303	0.1690	1.1143	0.6875
	Lab—Extra	0.2327	0.1719	1.1167	0.6989
T2	Lab—Nil	0.2051	0.1329	0.7569	0.1704
	Lab—Extra	0.2047	0.1321	0.7546	0.1668
T3	Lab—Nil	1.0929	1.0223	4.6249	4.0655
	Lab—Extra	0.7230	0.6519	1.3903	0.8167

6. Discussions

Our results show that low physician utilization has the largest positive impact on the EDLOS, VLOS and TFC of all patients. The obvious solution is to increase the number of physicians within the scarcity and cost of well-trained physicians. The other alternative is to improve the use of physicians' time using techniques, such as lean and six sigma process improvement tools, to eliminate unnecessary wastes and non-essential tasks, and improve the execution of essential tasks performed by physicians during consultations. Steps can also be taken to reassign essential tasks to other qualified personnel supporting the physicians. These initiatives can effectively increase the physicians' capacity to serve more patients and each patient faster, and reduce the EDLOS, VLOS and TFC of all patients.

Apart from the criticality of physician as a resource, choosing the right triage process can significantly affect the EDLOS, VLOS and TFC of different groups, especially at high physician utilization. The triage process T3 is better than T2, and T2 is better than T1 in reducing the EDLOS and VLOS of patients who are likely to encounter longer EDLOS and VLOS because of laboratory services. Both T2 and T3 can significantly reduce the EDLOS and VLOS of patients who require laboratory services with a marginal increase in the EDLOS and VLOS of patients who do not require laboratory services. While T3 offers patients who require laboratory services the smallest EDLOS and VLOS, there may be concerns over the ability of triage nurses in ordering the right tests and the longer TFC because of waiting for the laboratory results before first consultations with physicians. Wrong ordering of tests is not only a waste of resources but may cause further delays if new tests are required by the physicians. If such a concern exists, the T2 triage process is likely a better starting point. The triage nurses in T2 do not prescribe any laboratory tests, but simply assign higher priority to patients who require laboratory services to consult the physicians earlier. Consequently, the triage process T2 not only reduces the EDLOS, VLOS and TFC of such patients significantly but also avoids the risk of triage nurses ordering the wrong tests. Subsequently, over time, the triage nurses in a T2 triage process may be trained to implement a hybrid T2/T3 triage process for patients with certain clinical presentations that do not require speedy first consultations with physicians. For instance, accurate advanced triage protocols are available for certain clinical presentations such as patients with extremity injuries, suspected pneumonia and myocardial infarction. A T2 triage process can hence evolve over time into a hybrid T2/T3 triage process that is empowered to order certain tests for patients with clinical presentations that do not require speedy first consultations with physicians. The hybrid triage process can then further evolve over time into a full T3 triage process that empowers the triage nurses to order all tests for patients whose times to first consultations are not expected to affect their treatment outcomes.

The provision of different extra resources within the ED affects the patient groups differently. Extra triage capacity is positive for all patient groups and results in significantly shorter EDLOS, VLOS and TFC for all patients, especially at high physician utilization. In contrast, extra laboratory capacity has little or no impact on patients who do not require laboratory services, but is highly beneficial for patients who require services from dedicated laboratories. As most dedicated laboratories operate with one or limited number of servers, any attempt to operate such facilities with little or no extra capacity can result in unacceptable delays for patients who require services from such laboratories. In contrast, the provision of extra shared laboratory capacity is less important for patients who use the shared laboratories. The presence of requests with different priority allows a shared laboratory to serve requests from the emergency department promptly, and maintain high utilization at the same time by serving low priority requests during lull periods. A shared laboratory thus offers significant advantage over a dedicated laboratory. If dedicated laboratories are used, they should be used only for the most acute and immobile patients and operated with extra capacity at most times for quick response.

7. Conclusions

This study examines the impact of three alternative triage processes, shared versus dedicated laboratories, and different utilization of physicians, triage nurses and laboratories on the performance of emergency departments using a generic simulation model of EDs. Our simulation model is built upon a set of conservative assumptions such that implementations of our findings in actual EDs are expected to witness improvements that exceed those reported in our results. Our findings thus provide useful and general insights that can be implemented across different EDs to substantially improve their performance.

Useful insights are noted for managing the factors affecting the EDLOS, VLOS and TFC of different patient groups. At low physician utilization, the benefit of advanced triage processes and extra triage capacity is relatively muted. However, at high physician utilization, choosing the right triage process and extra triage capacity can significantly improve the ED performance. At high physician utilization, extra triage capacity offers the largest improvements in EDLOS, VLOS and TFC for patients who do not require laboratory services. For patients who require services from shared laboratories, an advanced triage process such as T2 and T3 and extra triage capacity offer the largest improvement in EDLOS and VLOS. When both are implemented together, the shared laboratory is, interestingly, able to handle the ED requests promptly without extra laboratory capacity. In contrast, the dedicated laboratory is much less able to handle surges in ED requests even with extra laboratory capacity. To improve the EDLOS and VLOS of patients who require services from dedicated laboratories, extra laboratory capacity in the dedicated laboratory offers the largest improvements.

Future research on emergency departments may proceed in different directions. One obvious direction is to evaluate our results for specific EDs prior to actual implementations. Although the scale of effects may differ, the direction of effects is expected to remain the same. Another possibility is an investigation of excessive waiting times on patients who leave the emergency department without service. This can be done with a similar generic simulation model, or based on configurations of specific EDs. The number of patients leaving without service is a pertinent measure of performance and is known to affect patients' outcomes, particularly patients who return after a short time interval when their conditions deteriorate. This behavior can be incorporated into a simulation model for further analysis. The effects of inaccurate triaging of patients can also be modeled explicitly and analyzed using simulation.

References

[1] L.B. Holm, F.A. Dahl. Using soft systems methodology as a precursor for an emergency department simulation model. OR Insight, 24 (3) (2011), pp. 168–189

[2] R.M. Cowan, S. Trzeciak. Emergency department overcrowding and the potential impact on the critically ill. Crit. Care, 9 (3) (2005), pp. 291–295

[3] D.P. Andrulis, et al. Emergency departments and crowding in United States teaching hospitals. Ann. Emerg. Med., 20 (9) (1991), pp. 980–986

[4] E.J. Carter, S.M. Pouch, E.L. Larson. The relationship between emergency department crowding and patient outcomes: A systematic review. J. Nurs. Scholarship, 46 (2) (2013), pp. 106–115

[5] G.D. Innes, et al. Does physician order entry reduce emergency department length of stay in overcrwoded emergency department? Acad. Emerg. Med., 10 (5) (2003), pp. 491–494

[6] J.M. Walrath, R. Tomallo-Bowman, J.M. Maguire. Emergency department: Improving patient satisfaction. Nurs. Econ., 22 (2) (2004), pp. 71–74

[7] C.C. Chen, et al. Key drivers for the continued use of RFID technology in the emergency room. Manag. Res. News, 31 (4) (2008), pp. 273–288

[8] S.J. Shim, A. Kumar. Simulation for emergency care process reengineering in hospitals. Bus. Process Manag. J., 16 (5) (2010), pp. 795–805

[9] R.W. Derlet, J.R. Richards. Overcrowding in the nation's emergency departments: complex causes and disturbing effects. Ann. Emerg. Med., 35 (1) (2000), pp. 63–68

[10] R.L. Gardner, et al. Factors associated with longer ED lengths of stay. Am. J. Emerg. Med., 25 (6) (2007), pp. 643–650

[11] B.R. Asplin, et al. A conceptual model of emergency department crowding Ann. Emerg. Med., 42 (2) (2003), pp. 173–180

[12] A.J. Forster, et al. The effect of hospital occupancy on emergency department length of stay and patient disposition Acad. Emerg. Med., 10 (2) (2003), pp. 127–133

[13] T.C. Chan, et al. Impact of rapid entry and accelerated care at triage on reducing emergency department patient wait times, lengths of stay, and rate of left without being seen. Ann. Emerg. Med., 46 (6) (2005), pp. 491–497

[14] K.E. Kocher, et al. Effect of testing and treatment on emergency department length of stay using a national database. Acad. Emerg. Med., 19 (5) (2012), pp. 525–534

[15] C. Chong, et al. Is Emergency Department length of stay associated with inpatient mortality? Australas. J. Aging, 32 (2) (2013), pp. 122–124

[16] N.T. Mowery, et al. Emergency department length of stay is an independent predictor of hospital mortality in trauma activation patients. J. Trauma., 70 (6) (2011), pp. 1317–1325

[17] A.J. Singer, et al. The association between length of emergency department boarding and mortality. Acad. Emerg. Med., 18 (12) (2011), pp. 1324–1329

[18] B. Bursch, J. Beezy, R. Shaw. Emergency department satisfaction: what matters most? Ann. Emerg. Med., 22 (3) (1993), pp. 586–591

[19] K.V. Iserson, J.C. Moskop. Triage in medicine, Part I: Concept, history, and types. Ann. Emerg. Med., 49 (3) (2007), pp. 275–281

[20] J.G. Cronin. The introduction of the Manchester triage scale to an emergency department in the Republic of Ireland. Accid. Emerg. Nurs., 11 (2) (2003), pp. 121–125

[21] R. Beveridge, et al. Canadian emergency department triage and acuity scale: Implementation guidelines. Can. J. Emerg. Med., 1 (3 SUPPL.) (1999), pp. S1–S24

[22] C.M.B. Fernandes, et al. Five-level triage: A report from the ACEP/ENA five-level triage task force. J. Emerg. Nurs., 31 (1) (2005), pp. 39–50

[23] M.E.H. Ong, et al. Prediction of cardiac arrest in critically ill patients presenting to the emergency department using a machine learning score incorporating heart rate variability compared with the modified early warning score. Crit. Care, 16 (3) (2012), p. R108

[24] J.L. Wiler, et al. Optimizing emergency department front-end operations. Ann. Emerg. Med., 55 (2) (2010), pp. 142–160

[25] D.W. Spaite, et al. Rapid process redesign in a university-based emergency department: Decreasing waiting time intervals and improving patient satisfaction. Ann. Emerg. Med., 39 (2) (2002), pp. 168–177

[26] H.W. Meislin, et al. Fast track: Urgent care within a teaching hospital emergency department: Can it work? Ann. Emerg. Med., 17 (5) (1988), pp. 453–456

[27] H.K. Simon, et al. Fast tracking' patients in an urban pediatric emergency department. Am. J. Emerg. Med., 14 (3) (1996), pp. 242–244

[28] L.C. Hampers, et al. Fast track and the pediatric emergency department: Resource utilization and patient outcomes. Acad. Emerg. Med., 6 (11) (1999), pp. 1153–1159

[29] L. Graff, et al. Triage of patients for a rapid (5-min) electrocardiogram: A rule based on presenting chief complaints. Ann. Emerg. Med., 36 (6) (2000), pp. 554–560

[30] A.J. Singer, M.J. Stark. Pretreatment of lacerations with lidocaine, epinephrine, and tetracaine at triage: A randomized double-blind trial. Acad. Emerg. Med., 7 (7) (2000), pp. 751–756

[31] M. Fry. Triage nurses order x-rays for patients with isolated distal limb injuries: A 12-month ED study. J. Emerg. Nurs., 27 (1) (2001), pp. 17–22

[32] P. Campbell, et al. Implementation of an ED protocol for pain management at triage at a busy level I trauma center. J. Emerg. Nurs., 30 (5) (2004), pp. 431–438

[33] J.J. Cooper, E.M. Datner, J.M. Pines. Effect of an automated chest radiograph at triage protocol on time to antibiotics in patients admitted with pneumonia. Am. J. Emerg. Med., 26 (3) (2008), pp. 264–269

[34] F. Subash, et al. Team triage improves emergency department efficiency. Emerg. Med. J., 21 (5) (2004), pp. 542–544

[35] J.P. Travers, F.C.Y. Lee. Avoiding prolonged waiting time during busy periods in the emergency department: Is there a role for the senior emergency physician in triage? Eur. J. Emerg. Med., 13 (6) (2006), pp. 342–348

[36] B.R. Holroyd, et al. Impact of a triage liaison physician on emergency department overcrowding and throughput: A randomized controlled trial. Acad. Emerg. Med., 14 (8) (2007), pp. 702–708

[37] A.S. Kiran, M.L. Smith. Simulation studies in job shop scheduling, I: A survey. Comput. Ind. Eng., 8 (2) (1984), pp. 87–93

[38] A.S. Kiran, M.L. Smith. Simulation studies in job shop scheduling, II: Performance of priority rules. Comput. Ind. Eng., 8 (2) (1984), pp. 95–105

[39] K.K. Yang. A comparison of cross training policies in different job shops. Int. J. Prod. Res., 45 (6)

[40] K. Jensen, T. Mayer, S. Welsh. Leadership for Smooth Patient Flow. Health Administration Press, Chicago, IL (2007)

[41] G. Dipender, et al. Laboratory sample turnaround times: do they cause delays in the ED? J. Eval. Clin. Pract., 18 (2012), pp. 121–127

[42] G.J. Fermann, J. Suyama. Point of care testing in the emergency department. J. Emerg. Med., 22 (4) (2002), pp. 393–404

[43] P.K. White Jr., A survey of data resources for simulating patient flows in healthcare delivery systems, in: Proceedings of the Winter Simulation Conference, 2005.

[44] R. Ceglowski, L. Churilov, J. Wasserthiel. Combining data mining and discrete event simulation for a value-added view of a hospital emergency department. J. Oper. Res. Soc., 58 (2) (2007), pp. 246–254

[45] M.A. Badri, J. Hollingsworth. A simulation model for scheduling in the emergency room. Int. J. Oper. Prod. Manage., 13 (3) (1993), pp. 13–24

[46] J.T. Blake, M.W. Carter. An analysis of emergency room wait time issues via computer simulation. INFOR Inf. Syst. Oper. Res., 34 (4) (1996), pp. 263–273

[47] R. Konrad, et al. Modeling the impact of changing patient flow processes in an emergency department: Insights from a computer simulation study. Oper. Res. Health Care, 2 (4) (2013), pp. 66–74

[48] M. Garcia, C. Rivera, Reducing time in an emergency room via a fast-track, in: Proceedings IEEE Simulation Conference, 1995, pp. 1048–1053.

[49] J.E. Helm, S. Ahmadbeygi, M.P. Van Oyen. Design and analysis of hospital admission control for operational effectiveness. Prod. Oper. Manage., 20 (3) (2011), pp. 359–374

[50] M. Johnson, V. Capasso. Improving patient flow through the emergency department. J. Healthcare Manag., 57 (4) (2012), pp. 236–243

[51] L.C. Tang, S.W. Lam, T.-N. Goh. A tasks-based six sigma roadmap for healthcare services. Handbook of Performability Engineering, Springer London (2008), pp. 1011–1024

[52] W. Kelton, R. Sadowski, N. Swets. Simulation with Arena (5th ed.) McGraw-Hill, New York, USA (2010)

[53] A. Fletcher, et al. The DH accident and emergency department model: A national generic model used locally. J. Oper. Res. Soc., 58 (2007), pp. 1554–1562

[54] W. Abo-Hamad, A. Arisha. Simulation-based framework to improve patient experience in an emergency department. European J. Oper. Res., 224 (1) (2012), pp. 154–166

[55] T.J. Coats, S. Michalis. Mathematical modelling of patient flow through an accident and emergency department. Emerg. Med. J., 18 (3) (2001), pp. 190–192

[56] P.A. Salzarulo, et al. The impact of variability and patient information on health care system performance. Prod. Oper. Manage., 20 (6) (2011), pp. 848–859