Operations Research for Health Care 9 (2016) 29–39

Contents lists available at ScienceDirect

Operations Research for Health Care

journal homepage: www.elsevier.com/locate/orhc

Use of a simulation-based decision support tool to improve emergency department throughput

Chongsun Oh, April M. Novotny, Pamela L. Carter, Ray K. Ready, Diane D. Campbell, Maureen C. Leckie *

Lakeland Regional Health, 1324 Lakeland Hills Boulevard, Lakeland, FL 33805, United States

ARTICLE INFO

Article history:
Received 19 November 2014
Accepted 18 March 2016
Available online 12 April 2016

Keywords:
Emergency department
Discrete event simulation
Decision support system
Throughput time
Length of stay

ABSTRACT

A simulation based decision support model was used in the redesign of an emergency department (ED) with close to 180,000 visits per year. In order to accommodate high patient volumes at a single site ED, improving patient throughput time is necessary to maintain operational efficiency and to provide high quality patient care. A throughput time goal of arrival to departure under 3 h for 80% of ED patients was selected as the redesign project objective. Using discrete event simulation modeling, target areas for improvement are identified including optimized process flow, resource allocation and operational policies. Simulation modeling allows ED leadership to make decisions on operational changes using quantitative information of the impact of what-if scenarios on key performance measures. Based on simulation data results, changes in ED processes were implemented that resulted in 81% of patients having a length of stay in the ED of less than 3 h; a 30% improvement in average patient length of stay.

1. Introduction

The Lakeland Regional Health (LRH) is the busiest single-site emergency department (ED) in Florida with over 170,000 ED visits in 2012. Furthermore, the ED experiences annual increases in patient volume, which is predicted to rise by 10.7% in 2014 to 190,256 annual visits based on time series analysis using monthly volume data. In order to effectively manage an increasing rate of patient arrivals without increasing the size of the ED, reduction in the average length-of-stay (LOS) for ED patients is required. In this study, throughput time is defined as a patient's total LOS from arrival to departure from the ED. Patient throughput time has a significant impact on operational and economic efficiency as well as overall patient satisfaction, which is a measure of service quality. Increases in throughput time lead to longer wait times and increased rate of patients who leave without being seen by a professional medical practitioner (LWBS) [1].

The ED faces multifaceted challenges such as meeting community expectations, increasing patient visits, and improving patient throughput time while simultaneously controlling operational expenses, resource utilization, staff productivity and quality of patient care. Therefore, an eighteen month ED innovation project was initiated and led by a redesign team consisting of stakeholders such as senior hospital administrators, inpatient staff, ED staff, and members of supporting departments such as radiology, environmental, laboratory and industrial engineering. At the start of the project, the percentage of patients with LOS under 3 h was below 50%, which is far from the desired level of performance. Initial objectives of the redesign project included analysis of current ED processes and identification of target areas for improvement. A LOS goal of less than 3 h for 80% or more of ED patients was selected. It was determined that the project would also focus on maintaining high quality service, efficient resource utilization, and evaluation of alternatives for improvement prior to actual implementation. Complexities in the ED system, which is a dynamic environment with a high-level of human involvement and a large number of variables, e.g. staff schedules, number of beds and bed open hours (Ref. [2]), lead to uncertainty in implementation outcomes. Therefore, we realized there is a need for scientific approaches to decision making in the ED to estimate the expected performance impact of various alternatives by testing them without commitment of physical resources or interruption to service delivery.

To address the need for an ED decision support tool, we developed a discrete event simulation model of ED patient flow. The model was designed specifically to capture the performance measures, which are needed to identify underlying problems that are difficult to acquire from actual data. Utilizing this tool enabled the identification of opportunities for improvement, prediction

* Corresponding author.
E-mail address: maureen.leckie@myLRH.org (M.C. Leckie).

http://dx.doi.org/10.1016/j.orhc.2016.03.002
2211-6923/

of the impact of operational changes, and examination of the tradeoffs between various alternatives.

Academic studies using computer simulation as a research method in healthcare have recently increased in popularity [3]. Simulation models have been shown to be an effective tool for process modeling and improvement [4] as evidenced by over 100 publications on application of simulation to healthcare processes and systems. For example, simulation models have been used to identify sources of variability and improvement factors in an outpatient clinic setting [5]. A major area of application for simulation models is investigation of resource optimization and capacity planning including staff and resource scheduling, impact on utilization, and optimization of staffing levels [6–17]. Simulation modeling methods have also been used to study the effects of physical layout changes on LOS [18]. The impact of operational process changes, such as triage methods, on performance with a focus on patient throughput time has also been studied [19,20]. Simulation tools have been used to study the effects on patient waiting time of adding resources or altering admission rates [21,22].

Simulation models are well-suited to address problems in EDs where resources are scarce and patients arrive at irregular times [2]. However, there are few published studies on the use of simulation to model the complete operation of an emergency department. Many simulation studies in an emergency department setting only analyze optimization of staff allocation or consider a small number of key performance indicators, e.g. waiting time to see a doctor and throughput time, while performance measures such as resource utilization and productivity are rarely considered together with throughput time. Furthermore, there are no studies that investigate the entire scope of processes in a single-site ED of comparable volume (180,000 visits per year) using a fine-grained simulation model. Although there are many simulation-based studies, very few successful implementations have been reported. This indicates a lack of published research on simulation as a decision tool resulting in implementation of solutions recommended by the model. In contrast, in this study decisions supported by simulation model analysis were implemented in practice as a result of effective stakeholder engagement with ED simulation modeling.

Lessons learned from previous healthcare simulation studies [23,24] indicate a key factor for successful implementation of findings include establishing relationships with all relevant stakeholders and involving the individuals to be affected by a redesign of the ED. In this case, defining realistic project objectives, scope and deliverables according to a required timeline led to successful and timely implementation of simulation study findings. Also, it is important to note that after implementation, performance measures were monitored and the results linked to national metrics, which is another missing aspect of previous studies.

2. Methods

A framework was developed for a simulation-based decision support system to drive continuous improvement, which defines the fundamental methods of our ED redesign project (Fig. 2.1).

2.1. Simulation-based decision making framework

Unlike most ED simulation research based on problem solving, i.e. identifying problems followed by exploring possible solutions, our approach to ED redesign is goal-driven. A length-of-stay goal of under 3 h for 80% or more of the patient population was chosen. Consideration was also given to maximizing productivity and minimizing operational costs. Target areas that are important to achieving goals were identified and solutions for improvement in each target area were developed. Since ED operations consist of a large number of interactions among multiple departments that are highly complex, achieving a solid understanding of underlying problems is a significant challenge. Therefore, it was necessary to develop and apply a comprehensive decision support system to coordinate diverse staff and departments through a unified strategic approach with a common goal.

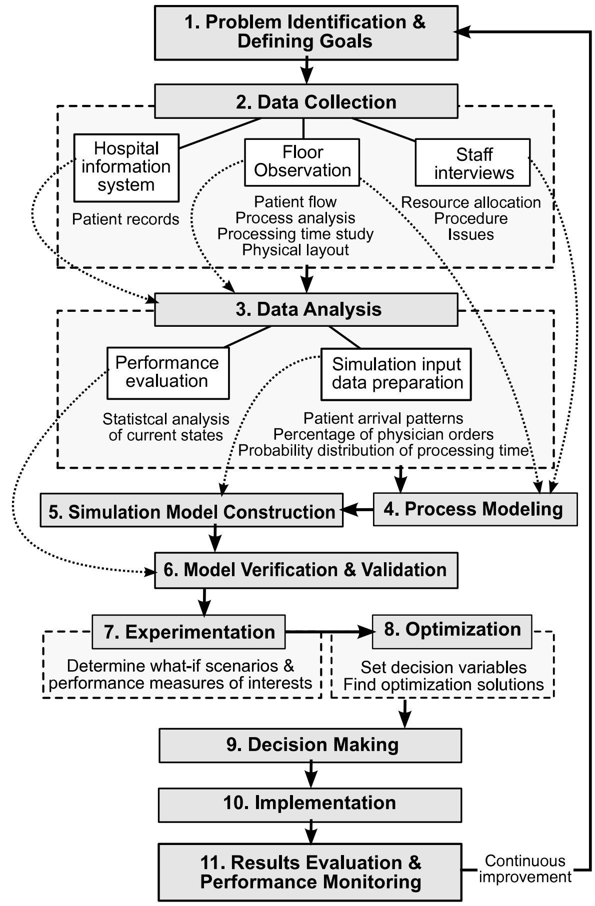


Fig. 2.1. Flow-chart overview of the framework for our simulation-based decision support system.

In order to identify and define problems, the simulation model begins with individuals entering the ED. It then proceeds to follow patients through processing and service delivery, and ends with patient departure from the ED. The ED population is generated based on patient arrival patterns during the winter prime season (January to May). The simulation model is constructed using a simulation software package (Rockwell Automation Arena). Data required to construct the simulation model was collected from floor observations, interviews with staff and practitioners, and patient records in the hospital information system. Key parameters from the hospital information system include mode of arrival, arrival time, disposition type, and admittance and discharge times. Due to potential lack of accuracy and consistency with data that had been input manually, appropriate data mining procedures to eliminate human errors and extract clean information preceded transfer of data to the simulation. Further data analysis was performed to obtain patient arrival patterns, patient volume by emergency severity index (ESI), proportions of physician orders for treatments, e.g. lab clinical, microbiology, X-ray, CT scan and ultrasound, and probability distributions for process times (details of the data analysis are discussed in Section 3.1). ED patient flows were mapped to a process model and used as input to a larger simulation model that includes sub-processes, resources

Table 2.1
The operations of resources of pods.

	Pod 1	Pod 2	Pod 3	Pod 4	Pod 5	Pediatric pod	Fast track
#beds	13	16	15	13	11	15	8
Hours	24	9–2 am	24	24	9–2 am	24	9–12 am
#CC beds	5	None	4	5	None	2	None

(e.g., staff, beds, and medical equipment), and entities, i.e. patients. Finally, logic linking different processes with a sufficient degree of detail to describe how entities are connected to resources, how resources are assigned, and the interconnections among various parts of processes were examined and incorporated into the model.

The final ED simulation model was constructed from the process model incorporating patient flows and verified by experts within the ED system. Predetermined key performance measures (Section 2.2.5) are used as performance outputs of the simulation model. In order to ensure simulation model accuracy, outputs were validated by comparison with actual key performance measure data including LOS, time interval between various processes, e.g. door-in to doctor and doctor to disposition, and treatment order volumes of laboratory tests and radiology examinations. After model verification and validation, the simulation can be used as a decision tool to investigate the impact of various alternatives (what-if scenarios) on key performance measures to predict the consequences of specific decisions.

A series of discussions among team members and extended data analysis helped to identify pain-points and develop ideas to smooth patient flow. As a result, several what-if scenarios to be explored were determined. Methods to improve pain-points primarily focused on process flow and resource allocation changes to achieve performance goals within system constraints. The results of what-if scenario experiments were then evaluated to provide guidance for selecting practical solutions to accomplish our performance goal. Finally, the selected process changes were implemented in the ED and implementation results evaluated. This decision support system framework is an iterative process to continuously improve the ED, and thus performance measures continue to be monitored in order to respond to any underperforming situations.

2.2. Description of ED process

2.2.1. Department layout

The ED consists of seven pods comprising geographically grouped rooms. Specifically, there is a single triage pod, five main pods serving adults, a single pediatric pod and one pod designated for adult patients with minor conditions that can be assessed and treated quickly, termed Fast Track. Adjacent to the main pods are two trauma rooms. With the exception of Pods 2 and 5, each adult pod has two beds designated for critical care (CC) patients and the remaining beds for universal patient bedding. Two pods (Pods 2 and 5) are open from 9 to 2 am and exclusively treat intermediate care (IC) patients. Bed capacities and open hours for each pod are summarized in Table 2.1.

A dedicated X-ray room is co-located with each Pod, but CT scan and ultrasound exam rooms are shared. In addition to treatment rooms for initial assessment, the fast track contains eight vertical spaces with recliner chairs for treatment of low-acuity ambulatory patients. The pod has two designated consultation rooms where a physician reviews examination results with patients and a nurse conducts the discharge process. Finally, eight pneumatic tube stations are located in the ED to transport samples to the laboratory.

2.2.2. Description of entities

Each ED patient belongs to one of four different groups; trauma, pediatric, adult main pod (intermediate or critical care), and adult fast track. These four groups share common as well as unique processes. Therefore, process models and model logic are defined separately for each group. In the simulation study, patients are not the only entities in the model, which also considers blood test samples, radiology tests and patient registration paperwork as entities. When test results and financial paperwork are completed, they are merged with their originating patient entity.

2.2.3. ED staff

Each main pod has a physician (MD) on nine hour shift and mid-level practitioners (MLP). MLPs can perform initial assessment and diagnosis, but are not permitted to perform a final assessment for determining disposition. Two MLPs are assigned to the main pods from 1 pm to 10 pm and from 10 pm to 7 am daily. On Tuesdays, Wednesdays and Thursdays, which are particularly busy days, an additional MLP is added serving the main pods. In contrast to the main pods, the pediatric pod has a 10-hour shift MD and the fast track has an 8-hour shift MD together with two 8.5 h shift MLPs. Aside from its pods, the ED has a variable number of triage nurses based on patient arrival patterns. Nurse shifts are predominantly 12-hours with some 8 hour-shifts. Main Pod 3, which has the most beds, has two 12-hour shifts and also an additional two 8-hour shift licensed practical nurses (LPN). At all times there is a nurse designated to the task of bed assignment, termed "bed traffic controller".

The ED radiology department has two radiologists between 10 am and 7 pm, one radiologist at all other times and an additional 3-hour shift radiologist is assigned every other week Monday to Friday only. Each radiology diagnostic and imaging area, such as X-ray, CT, and ultrasound, has 8-hour shift technologist and imaging assistants whose staffing levels vary according to a predetermined schedule. The ED also has two designated respiratory therapists (RTs) at all times. One RT is available for adult main pods, while another is assigned to the pediatric pod. Designated patient access representatives (PARs) perform registration processes and financial counseling for patients in the ED.

2.2.4. Patient flow analysis for model logic

The scope of the ED simulation model includes all patient flows from patient entrance to patient exit and completion of the bed cleaning process. In addition to multiple processes within the ED, the model also consists of processes in other departments providing services to the ED. This section provides high-level descriptions of typical patient flow in the ED (Fig. 2.2).

Patients can arrive at the ED either as walk-in or by emergency medical services (EMS), e.g. by ambulance. Upon arrival, walk-in patient condition is assessed by a pivot nurse (one of triage nurses) located in the main ED lobby, who determines the ESI level of the patient. Patients arriving by EMS are directly assigned to a bed where a RN completes the triage process including ESI determination. Walk-in patients comprise about 87% of the total volume, whereas air and ground EMS transports comprise the remaining 13%. Main and pediatric pods have dedicated triage nurses in a separate triage area. Based on ESI, patients are classified

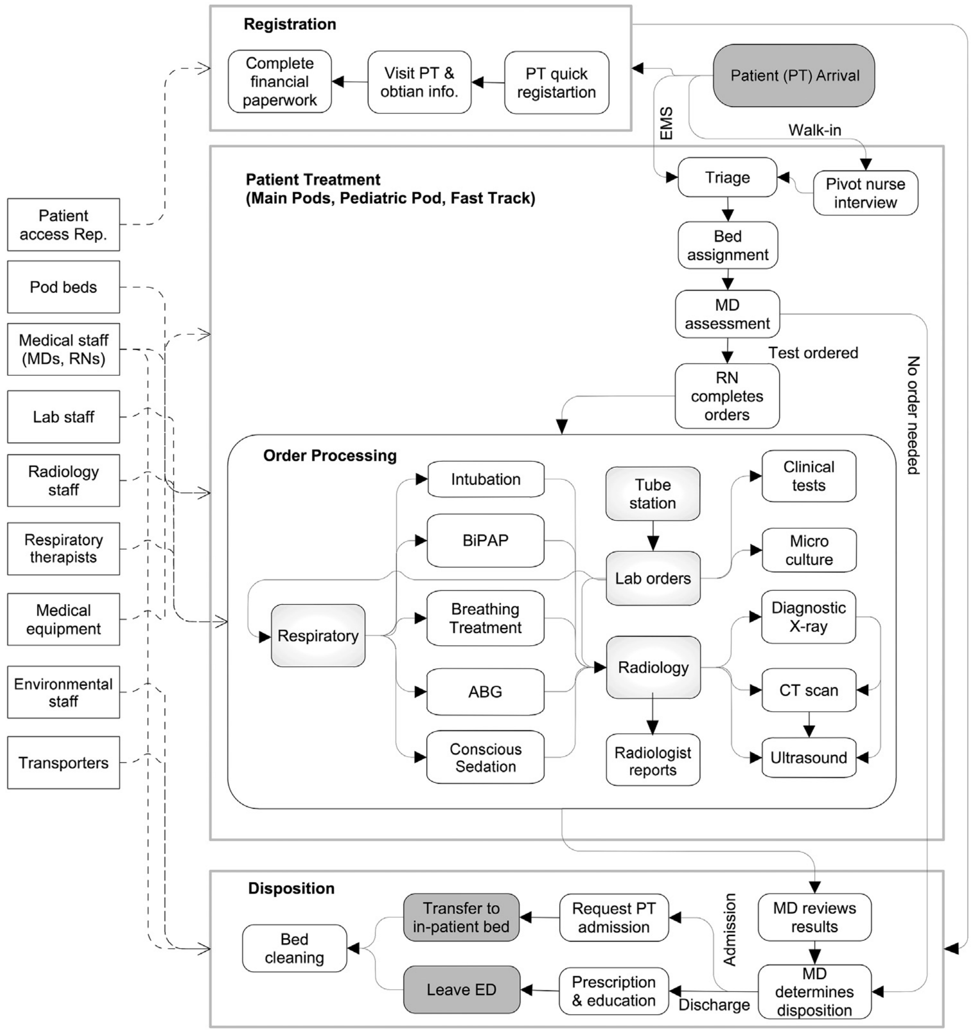


Fig. 2.2. High-level flow chart highlighting major processes taking place in the ED. *Abbrev.*: biphasic intermittent positive airway pressure (BiPAP), arterial blood gas (ABG), emergency department (ED).

according to the designations trauma, critical care, intermediate care or fast track.

Upon arrival to the ED, registration starts immediately in a process termed "quick registration" that involves entering patient information into the electronic medical records database. This process runs in parallel with other clinical service processes. After being seen by a pivot nurse, all walk-in patients go through an urgent triage process where initial assessment is performed by a triage nurse. During the urgent triage process, electrocardiogram testing is performed for patients meeting criteria for chest pain protocols. Triage is followed by assignment to an available bed in the appropriate pod. Alternatively, EMS patients bypass the triage area and are directly assigned to an available bed in the appropriate pod.

Triaged patients are assigned to a pod according to a queue discipline where emergent conditions (lower ESI) have priority over patients with non-urgent conditions (higher ESI). Patient allocation among the five main pods by the bed traffic controller follows a rotational basis in order to prevent individual pods from being overwhelmed with multiple simultaneous new patients. However, whenever a pod receives a CC patient in need of immediate emergency care, it is bypassed and put on hold for a period of 20 min. This rule is designed to allow the nurse and physician sufficient time to attend to the immediate needs of CC patients. Another exception occurs when a CC patient is to be assigned and the critical care bed limit is reached, the current pod is bypassed and the patient is placed in the next pod of the rotation cycle that has an available CC bed. These essential operational policies and staff protocols are fully incorporated into the simulation model.

Upon patient placement in a bed, a brief initial assessment is conducted by a nurse in conjunction with a physician assessment. For CC patients, two nurses are assigned during the initial stabilization if available. After assessment by a physician, treatment order(s) are entered into the electronic health record (EHR) and a nurse carries out tasks necessary to complete the order(s). For example, a nurse collects patient laboratory samples and walks to a nearby pneumatic tube station to send the samples to the in-house laboratory. Physician's orders may include radiological imaging such as X-ray, CT scan and ultrasound, laboratory analysis such as clinical blood and microbiology tests, and respiratory therapy treatments including arterial blood gas (ABG) tests, Biphasic intermittent positive airway pressure (BiPAP) ventilation, and intubation. Radiological imaging tests are performed either at the bedside using portable machines or in a designated room according to physician orders and patient condition. After laboratory orders are complete and radiology images are reviewed and dictated by a radiologist, test results are available for physician review during the final assessment process. In this process, disposition is determined to either discharge to home or to other facility (73% of patients), or admit the patient to the hospital (27%). After a physician determines disposition, the nurse completes a discharge process

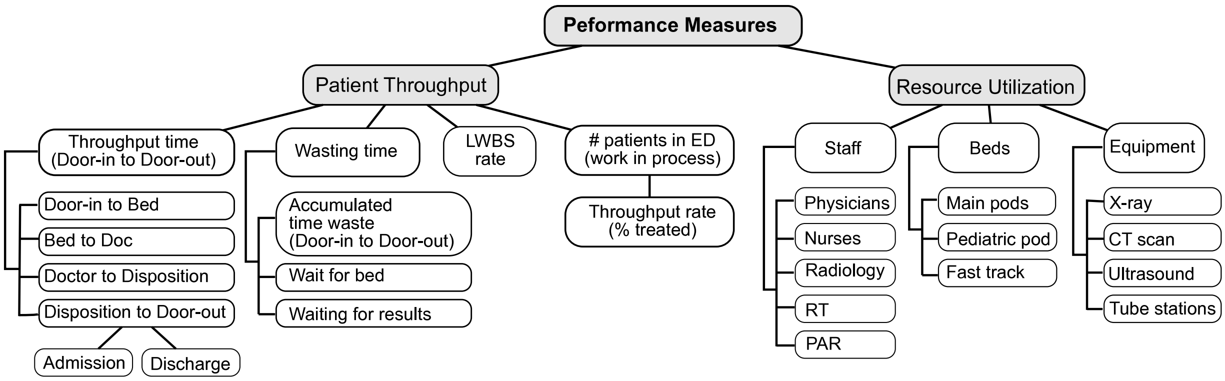


Fig. 2.3. Key performance measures assessed in the study. *Abbrev.*: left without being seen (LWBS), respiratory therapist (RT), and patient access representative (PAR).

that includes patient education and issue of prescriptions. In the case of admittance an attending physician is notified. Once an inpatient bed becomes available, the admitted patient is transported to an assigned unit by transportation staff. Finally, upon patient departure from the ED, environmental staff cleans the vacant bed.

2.2.5. Key performance measures for the ED

In the interest of improving patient throughput and resource utilization, appropriate key performance measures are selected. The first performance measure of patient throughput is average LOS, which is broken into several intervals such as door-to-bed, bed-to doctor, doctor to disposition and disposition to discharge/admission. Additionally, the accumulated time waste in the ED, LWBS rate and number of concurrent ED patients, which is equivalent to work-in-process (WIP) in a production setting, are measured. In this context, time waste refers only to time patients spend waiting excluding patient-involved processes such as waiting in bed for test results after all physician assessments and examinations are completed. In order to reflect current LWBS volume (less than 2% of total patient arrivals) in the simulation model, several criteria are applied to generate a LWBS population. Among patients who experience wait times greater than 30 min for either urgent triage, bed assignment in a pod or initial physician assessment, 20% leave the ED without being seen by a doctor.

In order to study resource utilization, all staff, beds, and medical equipment involved in ED processes are included in the model. Fig. 2.3 provides details of the key performance measures considered in our decision analysis.

3. Model development

3.1. Data collection and analysis

Analysis of empirical data is crucial for development of a robust simulation model that accurately represents ED processes. Data is collected from a combination of historical electronic patient records, observations of interactions between entities and resources, i.e. patients and staff, and interviews with practitioners and experts within the department. For ED volume estimates, patient arrival patterns are analyzed based on recent ED census data for January–May. This period is used to simulate high patient volume during the central Florida prime season. Arrival patterns are analyzed for each group and mode of arrival, such as walk-in and EMS, are both considered. Significant day-to-day and hour-to-hour variations in ED arrivals were found. Therefore, weekly arrival patterns representing the average number of arrivals per hour (Fig. 3.1) are analyzed and used in the simulation model.

To estimate the typical duration of a particular process, electronic data obtained from the hospital information system covering the last two fiscal years is collected. Additionally, over the course of several weeks, floor observations of patients and staff are performed. A probability distribution is fitted to each set of process times using chi-square goodness of fit hypothesis tests with a significance level of 0.05. For example, lab sample processing duration, i.e. time between sample arrival in the lab and test completion, is modeled using a Weibull distribution with shape parameter 1.33 and scale parameter 34.6 min. The time that pneumatic tubes carrying lab samples wait in tube stations until being transported to the lab is modeled using an Exponential distribution with mean of 52.1 s. In the case of process time data that does not fit well to an analytical distribution function, an empirical distribution is used.

Patient condition is determined by ESI levels and is grouped into categories such as CC (including emergent trauma patients), IC, and Fast Track. Depending on patient condition, processing times vary, such as initial assessment time for physician and nurse. Also, different model logic is incorporated in each sub-patient group, i.e. CC, IC, and Fast Track. The proportion of each patient group (combination of location and ESI) along with arrival mode is used as input settings to the simulation model (Table 3.1).

Data from the previous two fiscal years were obtained from the hospital information system and analyzed to find the proportion of physician orders for patient treatments. The data include six types of physician order: lab clinical blood test, microbiology culture test, diagnostic X-ray, CT scan, ultrasound imaging, and respiratory therapy. The latter includes intubation, BiPAP, breathing treatment, ABG and conscious sedation. For simplicity, all possible combinations of the six order types are grouped together under multiple orders. The proportions of multiple orders for main pods and Ped pod are 79% and 37%, respectively.

Average monthly order volumes including radiology, lab and respiratory tests are shown in Fig. 3.2(a). Due to a substantial increase in total order volume, radiology order volume for the simulation model is based on 2012 data, while the 2013 radiology volume is applied to what-if scenarios. In contrast, monthly order volumes for laboratory and respiratory remained consistent throughout the last two prime seasons. The percentages of radiology order combinations are shown in Fig. 3.2(b).

3.2. Model verification and validation

To ensure the credibility of simulation output results, model verification and validation was carried out by a combination of visual inspection of animations and by analysis of intermediate simulation output values. For model verification, after each model development phase, patient flows and model logic were examined and discussed with relevant experts including senior managers, nurses and physicians. This was to ensure patients follow expected care paths.

Table 3.1
Patient groups.

Initial bed location	% patients	Arrival mode		ESI (%)				
		Walk-in (%)	EMS (%)	1	2	3	4	5
Main pods	59	84.5	15.5	0.6	7.2	81.6	9.0	1.5
Pediatric pod	22	98	2.0	0.0	2.5	55.6	34.4	7.5
Fast track	19	100	0	0.0	0.0	7.7	63.8	28.4

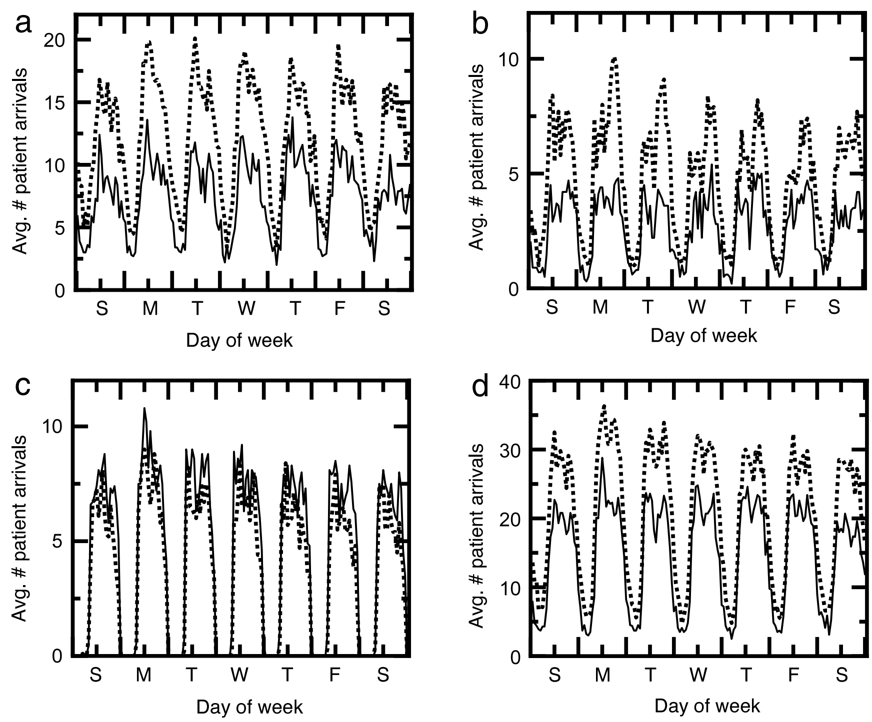


Fig. 3.1. Patient arrival patterns by hour. (a–c) Patient arrival patterns for main pods, pediatric pod, and fast track, respectively. (d) The arrival pattern of ED total patients (a, b and c combined). The solid line and dotted lines indicate patient arrivals in 2012 and 2013 prime season (January–May), respectively.

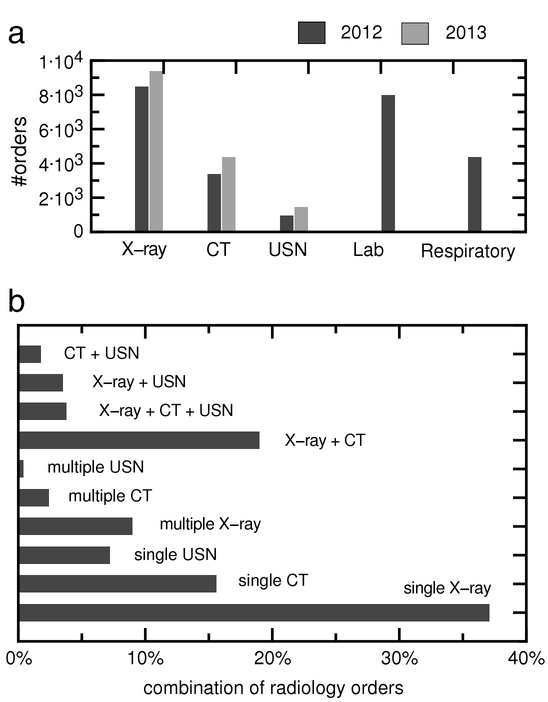
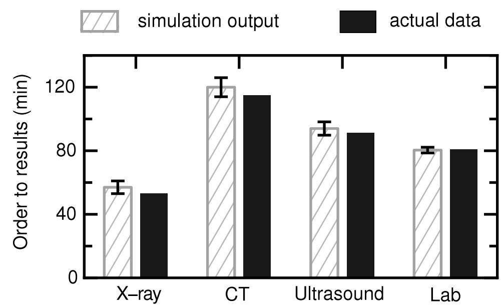


Fig. 3.2. Patient treatment orders (a) average monthly order volume and (b) radiology order combinations.

Output results of verified simulation models were then validated using a dual approach consisting of staff validation and comparison testing. Staff validation was performed for information that does not exist in electronic records and for data collected via staff interviews and floor observations. For outputs that have actual data in the hospital information system, for example inter-process time-stamps and order volumes, comparison testing consisted of comparing simulation model output against expected values. In these cases, a 95% confidence interval was used to validate the model. In addition to comparisons of the means, extreme statistics i.e., minimum and maximum values, were validated to evaluate distributions used in the model. Additionally, extreme statistics of key simulation outputs for which actual data does not exist, for example length of queue for radiologist review, were validated by judgments made by experienced ED staff. Examples of validation of order processing times, throughput performance measures and patient volume using comparison testing are summarized in Fig. 3.3.

3.3. *Identification of areas for improvement and proposed solutions*

One of the primary uses of the simulation model is identification of bottlenecks that cause patient flow delays. Key performance measures, such as time duration between processes, are examined in order to identify areas for improvement. A month-long simulation with five replications was run beginning on a Sunday at 12:00 am. Since the model begins with no entities and all resources idle, a two day warm-up period was used to ensure



Performance measures	Simulation output	Actual data	95% CI
%meet 3hr goal	44.9	44.4	(42, 48)
#patients in ED (WIP)	78.4	87	(69, 87)
LWBS (%)	4.03	3.94	(3.2, 4.9)
%admitted	25.8	26.5	(25, 26.5)
#patient arrivals (monthly)	14,133	14,208	(13,964, 14,302)

Fig. 3.3. Validation of simulation outputs against actual data. Error bars indicate 95% confidence interval.

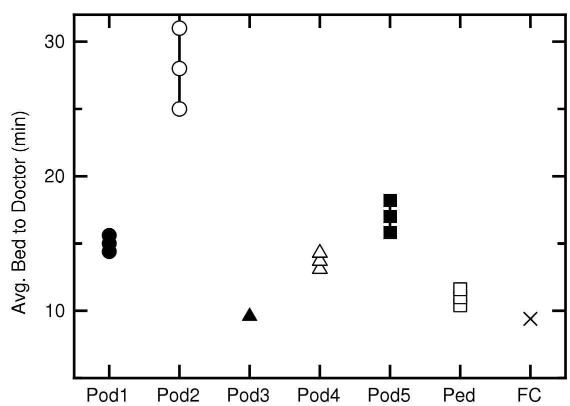


Fig. 3.4. Bed to doctor average duration. 95% confidence intervals indicated by upper and lower markers.

a steady-state simulation analysis. Following the simulation run, eight target areas were identified with the potential for significant improvement to patient LOS without dramatically altering the physical layout or clinical practices of the ED, and solutions involving limited resource increases, resource reallocation, patient flow redesign, and specific process time improvements were proposed for each area.

Target area 1: Main pod configuration

Our model indicates a significantly longer "Bed to Doctor" interval (average 28 min) in Main Pod 2 compared with other main pods (Fig. 3.4). To address this problem, reconfiguration of the main pods is tested by converting Pod 2b to a new ninth pod with a new dedicated physician.

Target area 2: Main pod bed allocation

Our model indicates the patient volume in each pod is skewed rather than being distributed evenly among pods. Fig. 3.5 shows Pod 3 has significantly higher patient volume than the other 24-hour pods (Pods 1 and 4), treating 28% of total main pod patients. Similarly, patient allocation is unbalanced in pods that are open from 9 to 2 am, e.g. Pod 2 has significantly higher patient volume than Pod 5. Considering that each of the main pods has dedicated physicians with similar levels of experience, reallocating the bed capacity is necessary to achieve a balanced patient allocation among pods and to achieve an even distribution of patients per physician. Pod 2 is open from 9 to 2 am and only accepts IC patients, which is split into two physical locations. Having a divided pod

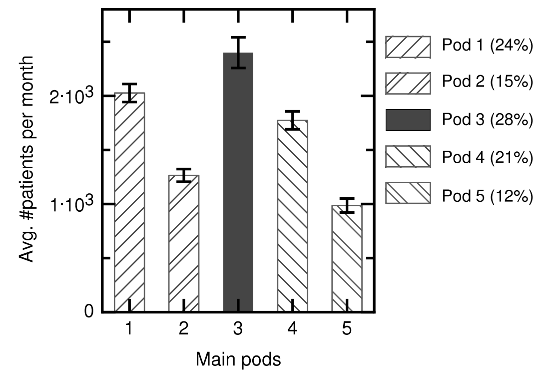


Fig. 3.5. Patient volume in main pods. Pod 3 includes mental health patient volume. The error bars represent 95% confidence intervals.

Table 3.2
New main pod configuration. After 1 am, each CC bed in Pod 9 is used for Pod 1 and Pod 4.

	Pod 1	Pod 2	Pod 3	Pod 4	Pod 5	Pod 9
#beds	12	12	11	12	12	10
Hours	24	9–1 am	24	24	9–1 am	9–1 am
#CC beds	2–3	2	2	2–3	2	2

configuration necessitates the physician travel frequently between the two locations. Also, despite having a large physical area and high number of beds (Table 2.1), Pod 2 shares the same physician capacity and allocation with other pods.

For Target area 2, we test reallocating bed capacity and permitting CC patients in all main pods, i.e. eliminate the restriction on CC patients in non-24-hour pods. This change necessitates each adult pod has universal bedding to allow all acuity levels to be assigned to the pod. The bed capacities and patient allocations to be tested are summarized in Table 3.2.

Target area 3: Radiology turnaround

The model identifies that patients endure an average 35 min delay for radiologist review of tests including X-ray, CT scan and ultrasound. This is a contributing factor to the door-to-door throughput time. The time-weighted average number of radiology tests in queue for radiologist review is found to be 9.5. In particular, the queue for radiologist review can be as long as 58 between 5 and 7 pm and occupies on average 91% of radiologist utilization. The model shows that despite having received their lab test results, patients with multiple orders, e.g. radiology tests (X-ray or CT scan) combined with a lab test, experience delays in final physician assessment due to unavailable radiology test results. Therefore, the waiting time for radiologist review needs to be reduced and methods to streamline the radiology process need to be identified.

The solution to Target area 3 includes (a) the addition of a radiologist during peak hours (5–7 pm) and (b) improvement of radiology technician workflow to more efficiently use the information system. This improvement includes using Wi-Fi capable electronic devices to upload ultrasound test data and installing computer stations in each pod to eliminate the need for CT technicians to use a central workstation. Implementation of seamless data transaction is expected to reduce technician processing time by 18%. Also, (c) reduction in adult patient CT scan oral contrast drink time is tested. Finally, (d) we increase radiologist use of self-editing dictation software for CT and Ultrasound reports.

Target area 4: Lab sample re-collection

The hospital laboratory recently implemented a full automation process, which enables batch and continuous flow processing. However, a 15% rate of lab sample re-collection at bedside persists. Re-collection hinders seamless lab process flow, and this factor was examined to study its impact on the overall lab process time. Most

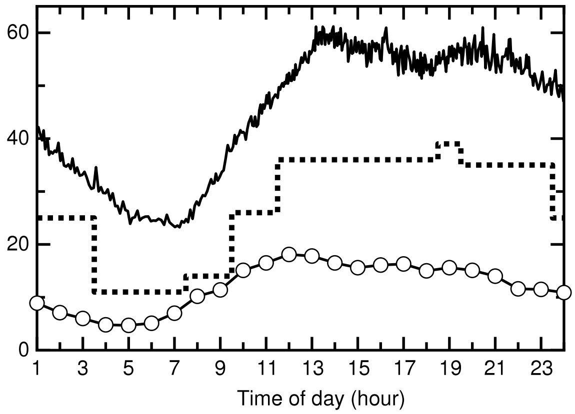


Fig. 3.6. Nurse staffing plan for the newly configured Main Pod with six pods. The dotted line indicates a proposed nurse staffing plan. Hollow circles and solid line represent Main Pod patient arrival patterns and the average number of patients concurrently in the Main pod (i.e. WIP), respectively, over a 30 day simulation repeated six times.

ED patients require multiple orders, i.e. combination of radiology and lab tests, with an average wait time of 32 min after one test (either radiology or lab) is complete. For example, 30% of total patients requiring a CT scan with contrast also require the results of a preceding lab blood test to determine if the patient can safely be administered contrast medium. Those patients wait 80 min on average for blood test results. Another example occurs with a combination order for a single X-ray scan and multiple lab tests where the radiology result is available, but a final physician assessment to determine disposition cannot proceed until all lab test results are available. These findings imply patient LOS reduction entails simultaneous improvements to both lab and radiology processes.

As an effort to reduce lab sample re-collection rate, a specimen quality task force was proposed and additional education for poor-performing nurses was established.

Target area 5: Main pod nurse staffing

In addition to ED throughput, resource utilization to evaluate staff productivity was examined. The model identifies that average utilization of nurses in main pods is 53% during night shift hours between 7 pm and 7 am. During this time frame, average patient arrivals are about 57% of the day shift (7 am–7 pm) patient volume, however nearly identical staffing levels are maintained. In order to maximize staff productivity while satisfying the LOS performance goal, re-design of the nurse staffing plans was necessary to reflect patient arrival patterns and changes in patient volume throughout the day.

Our proposed solution to Target area 5 involves re-design of nurse staffing to reflect the simulated output patient numbers in the ED at various times of the day in addition to patient arrival patterns. Also, we replace the LPN with an RN to expedite the discharge process. Fig. 3.6 shows a proposed nurse staffing plan alongside ED patient arrivals.

Target area 6: Pediatric MD staffing

The model indicates pediatric MD shift hours between 7 am and 5 pm exhibit high utilization during peak hours (80% utilization). This result corresponds with the period when a large number of patients experience prolonged wait times for final physician assessment. The model reveals the patient queue length abruptly increases after 9 am with above average length (6 patients) between the hours of 10 am and 2 pm on most days. Specifically, the average queue length exceeds 10 patients at 11 am and is maintained under 4 only after 4 pm. Therefore, it is apparent that current pediatric MD staffing levels are not able to accommodate peak hour demand and it is necessary to re-allocate pediatric physician capacity and shift hours.

Table 4.1
What-if scenarios for experimentation.

Scenario	Changes in ED operation
S1	Apply Target area 1, 2 and 3b solutions to base model
S2	Apply Target area 5, 6, 7 and 8 solutions to S1
S3	Apply Target area 3a solution to S2
S4	Apply Target area 4 solution (5% lab recollection rate) to S3
S5	Apply Target area 3c (70 min oral CT drink time), 3d (45% self-editing dictation use) and 4 (2% lab recollection rate) solutions to S3

To address Target area 6, Pediatric MD staffing levels were increased and MD schedules reconfigured. The new proposed MD staffing model uses 9-hour shifts, with two physicians between the hours of 1 pm and 1 am to improve wait times for a doctor during peak hours, and a single physician at all other times.

Target area 7: Physician availability

The model also identifies delays in the physician final assessment process. It is found that patients experience excess wait times (over 15 min on average) to see a physician for final assessment before disposition. This problem is most acute in the 24-hour pods. In order minimize this wait time, it is necessary to identify opportunities for reducing physician processing time thereby increasing her availability.

For Target area 7, patient flow in the triage process is altered by routing walk-in patients through an urgent triage prior to bed placement. It is estimated this change will reduce the physician time for initial assessment by 40%, and hence increase his availability for final assessments.

Target area 8: Inpatient bed turnaround time

The model indicates a delay between the time a physician completes final assessment and the time patient disposition is determined, i.e. the decision is made whether to discharge or admit a patient. Specifically, admitted patients experience a significant delay prior to being transported to a hospital bed. For main and pediatric pods, the average duration of disposition to discharge is 17 min, compared with an average duration of disposition to admission of 47 min. A primary cause of delay for admitted patients is the availability of hospital inpatient beds. This predicament highlights a situation where back-end processes involving patient flow outside the ED, e.g. inpatient bed turnaround time, need to be included in the scope of our strategy for ED performance improvement.

The proposed solution to Target area 8 is to reduce in-patient bed turnaround time to minimize the amount of time admitted ED patients occupy an ED bed prior to transfer to a hospital bed. Our target goal is under 10 min average wait time for patient transport to an in-patient bed. This goal corresponds to approximately 80% and 70% wait time reductions for adult and pediatric patients, respectively. In order to achieve this substantial reduction, extended performance improvement efforts such as redesign of staffing schedules and optimization of inpatient bed capacity were made in collaboration with the house bed management and transportation departments.

4. What-if scenario experimentation

Based on our bottleneck analysis to identify areas for improvement, five alternative "what-if" scenarios to achieve the stated LOS performance goal are determined by applying the suggested solutions described in Section 3.3 to the base model (Table 4.1). In this section, experimentation results for these scenarios are discussed, as well as target optimization variables affecting laboratory and radiology process times. Finally, the expected impacts of decisions are presented.

In scenario S1, where Pod 2b becomes new Pod 9 with an additional designated physician, a more even distribution of the

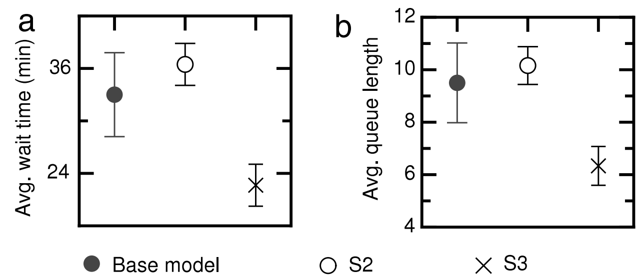


Fig. 4.1. Comparison of queue length and patient wait time for radiologist review. Error bars indicate 95% confidence intervals.

time interval between bed assignment to the patient being seen by a doctor (bed to doctor) is observed among the six main pods. Average times now range from 9.5 min to 12 min leading to a 32.5% reduction in the overall bed to doctor time. Additionally, scenario S1, which also reallocates Main Pod bed capacity among the new six pod configuration exhibits more evenly distributed patient volume among main pods. The average monthly patient volume for 24-hour pods 1, 3 and 4 is 1787 and 950 for 9 am-to-1 am pods 2, 5 and 9. There are no statistically significant differences in patient volume among the three same-hour pods. This result indicates the new bed capacity allocation plan avoids overburdening physicians belonging to a particular pod, which was a recurring problem in the previous five-Main Pod configuration (base model).

In order to increase night-shift nurse productivity while maintaining staffing levels, night-shift nurses were shifted to new peak hours that more closely follow patient arrival patterns (scenario S2). Simulated output shows this new nurse staffing schedule reduces the gap between day-shift and night shift nurse utilization by an average of 20%.

A new pediatric staffing plan that adds an additional physician results in 85% reduction in patient wait time to see their doctor for final assessment (20.5 min average decrease in wait time). Similarly, the effect of policy change to the urgent triage process where non-emergent adult walk-in patients receive an abbreviated triage prior to bed assignment, results in significantly reduced Main Pod patient wait times for both doctor initial and final assessment processes compared to scenario S1 with 50% and 27% average reductions, respectively. Based on experiment results, the new triage policy enables rapid doctor initial assessments, which are expected to contribute to overall throughput time improvements.

The total radiology order volume increased by 15% compared to the base model study. Previous changes applied to scenario S2 do not improve the radiologist review process. However, the experiment shows that both average wait time and average queue length of radiology image tests needing to be reviewed by radiologist in scenario S3 improve by 38% compared to the base model. This was achieved by adding another radiologist between 5 and 7 pm during peak hours (Fig. 4.1).

As a result of improved lab sample re-collection rate, which is reduced by 5% in scenario S4, a small improvement is observed in both the total accumulated wait time during patient stay in the ED and the percentage of patients with LOS under three hours. However, our performance goal is not achieved in this scenario (Fig. 4.2).

Considering most main pod patients receive multiple orders, e.g. a combination of lab and radiology tests, scenario S5 applies optimal values of the continuous decision variables within their specified ranges for throughput time improvement efforts involving both lab and radiology processes. For example, S5 variables include lab sample re-collection rate (1%–15%), CT oral drink time (45–90 min) and radiologist self-editing dictation use (0%–80%). Optimization is performed using the simulation model of scenario S3 with

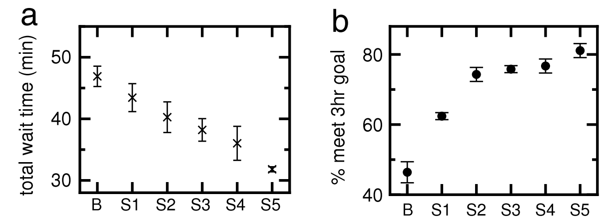


Fig. 4.2. Scenario comparison. (a) Average total accumulated wait time from door-in to door-out. (b) Average percentage of ED patients meet the 3 h LOS goal. Error bars represent 95% confidence intervals. The x-axis label "B" represents base model.

an objective of LOS under three hours for over 80% of patients. Using these constraints, several optimized solutions are found and the most realistic solution for implementation is selected, namely 2% lab sample re-collection rate, 70 min CT oral drink time and 45% radiologist self-editing dictation use.

As a result, scenario S5 achieves our throughput time goal with an average of 81% of patients going through the ED system in under three hours and all resources are utilized under 80% on average. Noticeably, main pod beds and radiologists, which were the two most heavily utilized resources (with over 80% utilization on average), exhibit improvements of 10% and 14%, respectively. Simulation outputs of what-if scenarios for key performance measures are presented in Table 4.2. Using the detailed performance measures, we are able to identify the impact of each scenario on both ED throughput and resource utilization, and to analyze their interactions.

5. Implementation results

What-if scenario analysis indicates that scenario S5 can achieve the LOS goal and the ED was re-designed accordingly. After a five month post-implementation period from January to May, performance data was collected for evaluation. To evaluate the forecasted ED volume applied to scenario S5, the forecast was compared against actual volume during the implementation period. The Mean Absolute Percentage Error (MAPE) was calculated to measure the forecasting model accuracy, which is 3.5% based on average monthly ED visits. Considering volatility of the ED volume data and our resource capacity, we concluded that a deviation of less than 5% is acceptable to construct reliable analysis of implementation results. Also, all operational processes and resources during the implementation period were maintained identical to those used in scenario S5. In other words, there were no additional changes made beyond the specific target solutions of scenario S5. Therefore, it is claimed that improvements found in post-implementation are direct results of our simulation-based study. The overall implementation results including LOS are summarized in Table 5.1.

After operating the ED with the suggested changes implemented, a reduction in LOS of 30% was measured thereby achieving our patient throughput performance goal. Since the full implementation, 81% of ED patients are treated and leave the ED in under three hours averaged over the five month period. This is an 80% improvement compared to performance prior to the ED redesign implementation. We also observed that the implementation helped the ED to significantly reduce the average LWBS rate from 2.8% to 0.3%. This result proves that improvement in LOS impacts the LWBS population rate, which can be considered as a qualitative performance measure in addition to the customary indicators such as patient satisfaction and quality of ED patient care [25].

As shown in Fig. 5.1, which represents the normalized LWBS performance measures and the percentage of ED patients meeting the three hour LOS goal, the LWBS rate decreases as the three hour throughput rate increases. These improvements constitute a significant achievement considering an increasing year to year

Table 4.2
Examples of simulation outputs on key performance measures. ±: percentage of improvement relative to the base model scenario, Main: Main Pods, Ped: Pediatric, FC: Fast Track. Staff utilization is based on the time spent with patients only. Note that a 7% increase in patient volume compared to the base model scenario is applied in S1–S5.

Key performance measures (monthly average)		Base	S1		S2		S3		S4		S5	
		avg	avg	±	avg	±	avg	±	avg	±	avg	±
ED throughput (h)	Door to Bed Main	0.40	0.39	−3	0.27	−33	0.25	−38	0.30	−25	0.24	−40
	Bed to Doc Main	0.26	0.19	−27	0.17	−35	0.17	−35	0.17	−35	0.17	−35
	Doc to Disposition Main	2.63	2.33	−11	2.28	−13	2.20	−16	2.12	−19	2.03	−23
	Disposition to Door-Out Main	0.50	0.44	−12	0.20	−60	0.20	−60	0.20	−60	0.20	−60
	Door In-to-Door Out Main	3.86	3.36	−13	2.85	−26	2.76	−28	2.77	−28	2.57	−33
	Door to Bed Ped	0.50	0.30	−40	0.27	−46	0.29	−42	0.23	−54	0.26	−48
	Bed to Doc Ped	0.16	0.17	+6	0.17	+6	0.18	+13	0.17	+6	0.18	+13
	Doc to Disposition Ped	1.93	1.61	−17	1.32	−32	1.28	−34	1.38	−28	1.24	−36
	Disposition to Door-Out Ped	0.32	0.27	−16	0.15	−53	0.15	−53	0.15	−53	0.15	−53
	Door In-to-Door Out Ped	3.04	2.35	−23	1.89	−38	1.88	−38	1.79	−41	1.81	−40
	Door In-to-Door Out FC	1.74	1.43	−18	1.03	−41	1.03	−41	1.04	−40	1.04	−40
	#patients in ED (WIP)	78.4	73.4	−6	64.0	−18	63.8	−19	69.3	−12	61.9	−21
	LWBS (%)	4.03	1.60	−60	0.50	−88	0.21	−95	1.07	−73	0.23	−94
	Accumulated wait time	0.78	0.72	−8	0.67	−14	0.64	−18	0.6	−23	0.53	−32
	% patients meet 3 h goal	44.9	62.4	+39	74.3	+65	75.8	+69	76.7	+71	81.0	+80
	Throughput rate (%)	95.9	98.1	+2	99.2	+3	99.6	+4	98.7	+3	99.6	+4
	Lab order to results	1.34	1.34	0	1.23	−8	1.24	−7	1.00	−25	0.92	−31
	X-ray order to results	0.95	0.89	−6	0.98	+3	0.75	−21	0.72	−24	0.73	−23
	CT order to results	2.00	2.25	+13	2.36	+18	2.12	+6	2.04	+2	1.78	−11
	Ultrasound order to results	1.56	1.88	+21	1.94	+24	1.70	+9	1.69	+8	1.56	0
Resource utilization (%)	Bed Main	88	90	+2	81	−8	81	−8	87	−1	79	−10
	Bed Ped	72	60	−17	58	−19	58	−19	57	−21	57	−21
	Bed FC	50	41	−18	35	−30	36	−28	38	−24	37	−26
	Physician Main	72	63	−13	53	−26	52	−28	52	−28	53	−26
	Physician Ped	70	57	−19	60	−14	61	−13	61	−13	61	−13
	Physician FC	56	63	+13	51	−9	51	−9	50	−11	53	−5
	Radiologist	80	76	−5	78	−3	69	−14	68	−15	69	−14

Table 5.1
Performance measures pre- and post-implementation. Improvement is observed in each of the three performance measures.

Performance measures	Pre-.	Post-.	Improvement (%)
Meet 3 h goal (%)	44	80.9	84
Patient LOS (min)	198	139	30
LWBS (%)	2.8	0.3	89
Lab order to results (min)	81	53	35

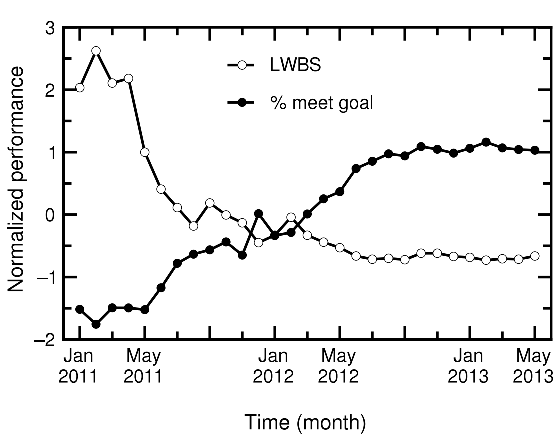


Fig. 5.1. Trends in LWBS and 3 h LOS goal performance over five month periods for different years.

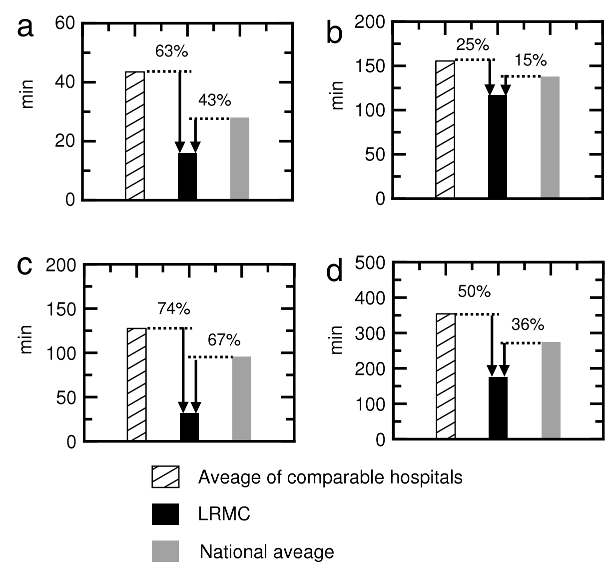


Fig. 5.2. ED performance comparison. (a) Average time patients spent in the ED before being seen by a healthcare professional (door-to-triage), (b) average time patients spend in the ED before being sent home (door-to-discharge), (c) average time patients spend in the ED after decision to admit as inpatient before leaving the ED (disposition-to-admission), (d) average time patients spend in the ED before being admitted to the hospital (door-to-admission).

trend in the number of ED visits. The ED patient volume during the post-implementation period increased by 7% compared to the same prime season period in the previous year.

We compared our implementation results with national metrics as well as other single-site EDs with similar patient volume ranging from 155,000 to 175,000 annual visits. Four comparable hospital EDs were selected from a list of the top 25 busiest hospital emergency departments in the United States ranked by number of emergency room visits in 2011 [26]. Performance and ED census data of other comparable hospitals are obtained from the US government website for Medicare [27]. As shown in Fig. 5.2, ED performance after implementing solutions recommended by this study exceeds that of other comparable hospitals as well as the national averages. Specifically, LRMC ED demonstrates a very efficient patient front-end process. "Door-to-doctor times" are 43% and 63% faster than the national and comparable hospital averages, respectively.

The time a patient spends in the ED from arrival until discharge is 117 min on average, which is 25% lower than the average of other comparable hospitals. In particular, significant outperformances are found for both the ED inflow process from door to triage and the ED outflow process for admitted patients. As shown in Fig. 5.2(a), the average time LRMC patients spend from arrival to being seen by a healthcare professional is 16 min, which is 63% less than the average of other comparable hospitals and 43% less than the national average. Most notable performance differences are found in Fig. 5.2(c), where LRMC patients spend 67% less time in the ED than the national average. This result leads to notably improved admitted patient throughput with 36% lower door-to-admission time compared to the national average (50% lower compared to comparable hospitals). Furthermore, our LWBS rate (0.3%) after implementation is significantly lower than the average 2% LWBS rate of the other four comparable hospitals. These comparisons clearly indicate that the performance improvement due to the ED redesign exceeds not only our internal performance goal, but also exceeds national standards.

6. Conclusion

A simulation-based decision support framework was effectively used to achieve a performance goal of LOS under three hours for over 80% of patients as part of an emergency department redesign project. Patient flow and interactions among multiple ED subprocesses were accurately emulated by a simulation model. Using the model, system bottlenecks were identified and ED managers were able to reveal key target areas that significantly impact average patient LOS. Decisions covered resource configuration, e.g. optimizing staff levels and bed capacity allocation, operational policies, e.g. upfront triage process for walk-in patients before bed assignment, and process improvement efforts such as minimizing delays in ED outflow to inpatient bed, reducing lab sample recollection rate, and increasing radiologist self-editing dictation use. After implementing our final decisions based on the simulation study, 81% of patient LOS times were reduced to less than 3 h. Continued use of this simulation model is predicted to lead to further improvements such as specific LOS goals for each bed location, i.e., over 80% of patients spend under 3 h in Main Pods, 1.5 h in Pediatric Pod and 1 h in Fast Track. Furthermore, inpatient admission rate will be investigated as an additional control variable in a future optimization study.

An ED simulation model has been demonstrated to successfully aid ED administrators to achieve a high quality patient care cycle while more efficiently using resources. The simulation-based decision making approach was well-received by ED managers and continues to be used for planning ED strategies. Finally, as a result of the successful outcome observed in the ED, simulation-based decision support systems will be applied to other departments across the hospital, such as surgery and oncology.

Acknowledgments

The authors gratefully acknowledge the generous assistance of and valuable information provided by ED staff and Data Science team members. The authors also thank industrial engineers Sheena Butts, Charles Winters and Derek Butts for their assistance in floor observations and process modeling.

The authors declare that they have no conflicts of interest.

References

[1] D.J. Medeiros, E. Swenson, C. DeFlitch, Improving patient flow in a hospital emergency department, in: Simulation Conference, 2008. WSC 2008, Winter, 2008, pp. 1526–1531.

[2] W. Abo-Hamad, A. Arisha, Simulation-based framework to improve patient experience in an emergency department, European J. Oper. Res. 224 (2013) 154–166. http://dx.doi.org/10.1016/j.ejor.2012.07.028.

[3] S.H. Jacobson, S.N. Hall, J.R. Swisher, Discrete-event simulation of health care systems, in: R.W. Hall (Ed.), Patient Flow: Reducing Delay in Healthcare Delivery, Springer, US, Boston, MA, 2006, pp. 211–252.

[4] J.B. Jun, S.H. Jacobson, J.R. Swisher, Application of discrete-event simulation in health care clinics: A survey, J. Oper. Res. Soc. 50 (1999) 109. http://dx.doi.org/10.2307/3010560.

[5] S. Chand, H. Moskowitz, J.B. Norris, et al., Improving patient flow at an outpatient clinic: study of sources of variability and improvement factors, Health Care Manage. Sci. 12 (2009) 325–340. http://dx.doi.org/10.1007/s10729-008-9094-3.

[6] A.K. Hutzschenreuter, P.A.N. Bosman, I. Blonk-Altena, et al. Agent-based patient admission scheduling in hospitals, in: Proceedings of the 7th International Joint Conference on Autonomous Agents and Multiagent Systems: Industrial Track. International Foundation for Autonomous Agents and Multiagent Systems, Richland, SC, 2008, pp. 45–52.

[7] S.S. Jones, R.S. Evans, An agent based simulation tool for scheduling emergency department physicians, in: AMIA Annu. Symp. Proc. 2008, 2008, pp. 338–342.

[8] M.A. Centeno, R. Giachetti, R. Linn, A.M. Ismail, A simulation-ILP based tool for scheduling ER staff, in: Simulation Conference, 2003. Proceedings of the 2003 Winter, vol. 2, 2003, pp. 1930–1938.

[9] L. Chin, G. Fleisher, Planning model of resource utilization in an academic pediatric emergency department, Pediatr. Emerg. Care 14 (1998) 4–9.

[10] M.A. Draeger, An emergency department simulation model used to evaluate alternative nurse staffing and patient population scenarios, in: Proceedings of the 24th Conference on Winter Simulation, ACM, New York, NY, USA, 1992, pp. 1057–1064.

[11] M.D. Rossetti, G.F. Trzcinski, S.A. Syverud, Emergency department simulation and determination of optimal attending physician staffing schedules, in: Proceedings of the 31st Conference on Winter Simulation: Simulation—A Bridge to the Future, vol. 2, ACM, New York, NY, USA, 1999, pp. 1532–1540.

[12] D. Sinreich, O. Jabali, Staggered work shifts: a way to downsize and restructure an emergency department workforce yet maintain current operational performance, Health Care Manag. Sci. 10 (2007) 293–308.

[13] M. Thorwarth, A. Arisha, P. Harper, Simulation model to investigate flexible workload management for healthcare and servicescape environment, in: Simulation Conference, WSC, Proceedings of the 2009 Winter, 2009, pp. 1946–1956.

[14] C.-L. Rau, P.-F.J. Tsai, S.-F.M. Liang, et al., Using discrete-event simulation in strategic capacity planning for an outpatient physical therapy service, Health Care Manag. Sci. (2013) http://dx.doi.org/10.1007/s10729-013-9234-2.

[15] N. Ahmad, N.A. Ghani, A.A. Kamil, et al., Evaluating emergency department resource capacity using simulation, Modern Appl. Sci. (2012) http://dx.doi.org/10.5539/mas.v6n11p9.

[16] M.M. Gunal, M. Pidd, Understanding accident and emergency department performance using simulation, in: Proceedings of the 2006 Winter Simulation Conference, 2006.

[17] T.R. Rohleder, P. Lewkonia, D.P. Bischak, et al., Using simulation modeling to improve patient flow at an outpatient orthopedic clinic, Health Care Manag. Sci. 14 (2011) 135–145. http://dx.doi.org/10.1007/s10729-010-9145-4.

[18] S. Samaha, W.S. Armel, D.W. Starks, The use of simulation to reduce the length of stay in an emergency department, in: Simulation Conference, 2003. Proceedings of the 2003 Winter, vol. 2, 2003, pp. 1907–1911.

[19] L.G. Connelly, A.E. Bair, Discrete event simulation of emergency department activity: a platform for system-level operations research, Acad. Emerg. Med. 11 (2004) 1177–1185. http://dx.doi.org/10.1197/j.aem.2004.08.021.

[20] T. Ruohonen, P. Neittaanmaki, J. Teittinen, Simulation model for improving the operation of the emergency department of special health care, in: Simulation Conference, 2006. WSC 06. Proceedings of the Winter, December, pp. 453–458.

[21] C. Duguay, F. Chetouane, Modeling and improving emergency department systems using discrete event simulation, Simulation 83 (2007) 311–320. http://dx.doi.org/10.1177/0037549707083111.

[22] R.K. Khare, E.S. Powell, G. Reinhardt, M. Lucenti, Adding more beds to the emergency department or reducing admitted patient boarding times: which has a more significant influence on emergency department congestion? Ann. Emerg. Med. 53 (2009) 575–585. http://dx.doi.org/10.1016/j.annemergmed.2008.07.009.

[23] S.C. Brailsford, T. Bolt, C. Connell, et al. Stakeholder engagement in health care simulation, in: Simulation Conference, WSC, Proceedings of the 2009 Winter, 2009, pp. 1840–1849. http://dx.doi.org/10.1109/WSC.2009.5429190.

[24] J. Bowers, M. Ghattas, G. Mould, Success and failure in the simulation of an accident and emergency department, J. Simul. 3 (2009) 171–178. http://dx.doi.org/10.1057/jos.2009.5.

[25] S.K. Polevoi, J.V. Quinn, N.R. Kramer, Factors associated with patients who leave without being seen, Acad. Emerg. Med. 12 (2005) 232–236. http://dx.doi.org/10.1197/j.aem.2004.10.029.

[26] Modern Healthcare, 25 Busiest hospital emergency departments. Modern Healthcare, 2013.

[27] Medicare Hospital Comparison. http://www.medicare.gov/hospitalcompare/search.html (accessed 24.09.13).