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Mitigating overcrowding in emergency departments using Six Sigma and simulation: A case study in Egypt

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ABSTRACT

Overcrowding in emergency departments (EDs) is a serious problem that can harm patients and lead to negative operational and financial performances for hospitals. This paper integrates the Six Sigma methodology with discrete event simulation (DES) to guide improvement decisions, in which we target the reduction of overcrowding in EDs with a special attention on the medical equipment utilization and the influence of changing the medical equipment technology on patients' waiting time and consequently their satisfaction. The Six Sigma methodology, based on the "Define, Measure, Analyze, Improve, and Control (DMAIC)" format, is used to analyze the EDs overcrowding problem, diagnose its causes, and control the performance improvement plans. The DES is used within the "Improve" phase in order to provide a prognosis for the expected performance under the proposed improvement scenarios and to evaluate their effects on the ED performance measures. This research investigates the benefits of the application of the quality improvement methods in the Egyptian healthcare system which has different characteristics compared to developed countries. A case study in a private tertiary hospital is used in the current investigation. We propose process-based modifications that can help reduce the overcrowding problem, increase patient throughput, and reduce patient length of stay. The case study demonstrates the effectiveness of using the integrated Six Sigma-DES approach on reducing the ED crowdedness. The use of DES in the "Improve" phase provides inexpensive assessments of the improvement alternatives and eliminates the troubles associated with real system modifications.

1. Introduction

The emergency department (ED) is an acute care unit annexed to a healthcare facility in order to provide urgent medical treatments for unscheduled patients. Due to the unplanned nature of the patient admission, the ED must provide initial treatment for a broad spectrum of traumas, some of which may be of a life-threatening nature. This entails not only the ability to provide a high-quality medical service, but also the immediate availability of resources. When the demand is predominantly higher than the supply, crowding and maybe overcrowding ensues. It was reported in [1] that on average, the number of emergency visits exceeds the ED's capacity 35% of the time, resulting in overcrowding and congestion. Although no precise definition exists, ED overcrowding refers to an extreme excess of patients in the treatment areas, exceeding ED capacity and frequently necessitating medical care to be provided in ED hallways and other makeshift examination areas. In 2006, The American College of Emergency Physicians Crowding Resources Task Force adopted the following definition of ED crowding: "A situation in which the identified need for emergency services outstrips available resources in the ED".

The ED crowdedness is currently being measured by several scoring systems [1–4]; the most common is the National Emergency Department Overcrowding Scale (NEDOCS), which was developed by Weiss et al. (2004) [1]. The NEDOCS score measures the degree of congestion in EDs exploiting parameters such as waiting time, amount of sickbeds, number of hospitalized patients, number of emergency patients, and other parameters by using a regression model as shown in Eq. (1).

$$NEDOCS = 85.8(P_{bed}/B_t) + 600(P_{admit}/B_h) + 5.64W_{time} + 0.93A_{time} + 3.4R_n - 20 \quad (1)$$

where P_{bed} is the number of patients in licensed beds and overflow locations, such as hallway beds or chairs, B_t is the number of licensed treatment beds, P_{admit} is the number of admitted patients, B_h is the number of hospital beds, W_{time} is the waiting time for the last patient put into bed, A_{time} is the longest time since registration

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among boarding patients, and R_n is the number of patients connected on ventilators.

The NEDOCS score has no upper limit, but the greater the value of the regression equation is, the greater the degree of congestion will be [5]. The NEDOCS is divided into six levels related to ED crowding; Level 1 reflects the least crowded situation and Level 6 indicates the highest crowdedness (Dangerously overcrowded) state. More information about the NEDOCS and its levels can be found in [1]. The NEDOCS measure is used to identify the ED crowding level of our case study.

The main objective of this study is to improve the ED performance by reducing both the NEDOCS measure and the patient length of stay (PLOS) through changing the used medical equipment and implementing new technology. This improvement, in turn, will reduce the overcrowding and promote a greater patient satisfaction. In order to achieve such goal, the Six Sigma methodology is utilized to analyze the ED overcrowding problem and suggest possible process redesigns in the ancillary services and radiology department, accordingly. With the help of the discrete event simulation (DES) models that can be built to analyze and assess the impact of the implementations of the suggested system redesigns on the performance of the ED, the best-suggested process redesigns are promoted. A case study was carried out on a private tertiary hospital in Egypt in order to demonstrate the efficacy of the integrated Six Sigma-DES approach in solving the problem of ED overcrowding.

The rest of this paper is organized as follows. In Section 2, relevant literature is reviewed followed by a description of the integrated Six Sigma-DES approach in Section 3. The work environment and conditions related to the studied case are presented in Section 4. In Section 5, the implementation of the integrated approach is demonstrated, followed by the conclusions in Section 6.

2. Literature review

A literature review is provided in [6] on the research work that addressed the overcrowding problem in EDs from perspective causes, effects, and solutions. That work is of an analytical nature, where researchers analyze the overcrowding problem and its different causes and impact on PLOS and the ambulance diversion. In addition, Magid et al. (2004) [7] and Pines et al. (2011) [8] studied the consequences of the ED crowding and the implications of interventions. On one hand, they showed that although it is widely assumed that ED crowding leads to serious quality problems, they have generally lacked data to support such a contention. There is also a gap in the knowledge about why errors increase within crowded EDs [8,9]. On the other hand, Magid et al. (2004) [7] illustrated that timeliness of ED care can be compromised under conditions of high ED crowding. Pines et al. (2011) [8] pointed out that an investigation is needed to study evidence linking stress to patients waiting to be seen. Also, Bernstein et al. (2009) [9] added that ED crowd is connected with waiting times and researchers indicated that waiting times as long as 6 h have been associated with higher rates of ''leaving without being seen''. Furthermore, Bernstein et al. (2009) [9] and Pines et al. (2011) [8] mentioned that the consequences of ED crowding are grave, including increasing morality.

The solutions to the overcrowding problem are classified in [6] into three approaches. The first approach seeks to increase the medical staff levels to match the increasing demand. The second approach diverts away the non-urgent referrals and ambulances in order to reduce the demand on emergency room. The third approach utilizes operations research (OR) techniques to increase the efficiency of the ED and therefore reduce the overcrowding. Also, the role of effective leadership and management in crowding interventions is critical and is often overlooked as a relevant factor [8].

The operations research-industrial engineering (OR-IE) techniques make use of the computational and modeling methods to improve the system efficiency. Some of these techniques include process re-engineering, scheduling, optimization, process and quality improvement, cost analysis, simulation and flow analysis and many other techniques that can be very valuable in solving the ED overcrowding problem. The current research does not only follow the third approach (i.e., OR) but also utilizes two of the OR-IE techniques, namely discrete even simulation and continuous quality improvement to improve the performance of ED.

2.1. Simulation in EDs

Since EDs are complex and highly dynamic systems, the simulation technique is favored because it does not require restrictive assumptions or simplifying generalizations, which are commonly found in analytical approaches such as queuing theory. In DES, the operation of a given system (i.e., ED, in our case) is modeled as a discrete sequence of events in time. This allows to study the behavior of the system under various circumstances through the implementation of the suggested model modifications instead of a rather costly realization of such modifications in real systems. Moreover, DES is different from other simulation methods, such as system dynamics [10,11], as it allows for constructing sophisticated models to any level of detail as needed. Hence, most studies utilized DES to model and analyze ED performance using different DES languages and software packages such as SLAM [12,13], SIMAN [14,15], SIMUL8 [16], Arena [17,18], ProModel [19] and MedModel [20]. In fact, the diversity of the simulation software used in this specific application indicates that there no specific technical requirements in the simulation software that would oblige the use of one over the others. In the current study, we opted to use SIMUL8 software [21] as it provides a simple interface that facilitates building and verifying the model.

Paul et al. (2010) [22] provided a systematic review of the simulation studies conducted on overcrowding in EDs from 1970 until 2006. Their review showed that the most commonly addressed performance objectives are minimizing operating costs, increasing competitiveness and efficiency, optimizing processes, and improving the quality of the provided service. The researchers who addressed the improvement of the quality of service considered the reduction of overcrowding by reducing both the patient waiting time and PLOS. However, to the best of our knowledge, no previous study has explicitly considered improving the overcrowding score, while this study does.

Simulation studies on EDs provided several improvement insights through three main tracks: leveling resources, improving processes, and varying external parameters affecting EDs [22]. Resource leveling included varying spaces such as the number of available beds or rooms [11,18], varying the number of ED staff [12,13,17,23–25], varying the number of supporting staff [15,17,26,27], and varying the number of equipment used in EDs [18,27]. Improving processes considered designing alternative routes for patient movements through the ED areas and facilities [23,28], and changing priorities given to special types of patients [12,15]. Varying external parameters affecting EDs included varying patient demand by scheduling non-emergency patients [29], and varying number of beds in different locations or units of a hospital [17,30,31]. This study exploits the improving processes approach in order to improve the ED performance and raise patient satisfaction.

Recent simulation studies were combined with other IE production improvement methods to guide improvement decisions. For example, throughput analysis and bottleneck identification were adapted to develop what-if scenarios in order to improve the ED performance in [32]. Through the detection of the bottlenecks, the optimal numbers of human and equipment resources can be determined and consequently, leveling resources can be fulfilled. Also DES and optimization algorithms were combined to determine the most suitable staff number, which maximized the patient throughput [33]. Also, a simulation-based decision support system (DSS) was developed in [34,35] to improve the quality of service in EDs. A new process modeling approach is proposed to analyze patient flow in relation to work flow of medical stuff to help identify bottlenecks and inefficient distribution of resources. The proposed approach was applied to an ED of an academic teaching hospital in Dublin. It was claimed that the proposed DSS based on simulation can offer a higher degree of confidence in the interpretation of simulation results.

The Lean manufacturing concept was applied to healthcare systems in order to eliminate the various types of waste in hospitals by minimizing non-value added activities. Khurma et al. (2008) [36] investigated a variety of Lean manufacturing tools, such as Cycle Time Analysis, Work Combination Charts, Cause and Effect Matrix, Fish-bone Diagram, and Affinity Diagram in order to analyze the ED overcrowding problem. Then DES was used to convey the gathered information from Lean manufacturing tools to visual forms to perform comparative analyses between the different improvement suggestions. Additionally, Sharma et al. (2007) [37] applied the Lean principles to the service management process in EDs of six hospitals in order to detect the value and non-value added activities. A simulation model guided by the Lean principles was built to optimize the size of the staff in different sub-processes of the service management process, in order to overcome and eliminate the trial and error approach.

2.2. Continuous quality improvement in EDs

Continuous Quality Improvement (CQI) is a quality management approach that focuses on continuously enhancing the processes within an organization with an eye on improving customer satisfaction. Six Sigma is a systematic and statistics-based CQI methodology, which is based on the philosophy of reducing the variation and activities (e.g., non-value added) that result in long cycle times, high cost, and poor outcomes. Six Sigma utilizes the "*Define*, *Measure*, *Analyze*, *Improve*, and *Control* (DMAIC)" improvement cycle of traditional CQI techniques in order to achieve the variation reduction targets. A process that operates under true Six Sigma levels produces acceptable quality levels over 99.9996% of the time.

On the one hand, Six Sigma methodology can be applied in healthcare systems to improve their financial and operational performances that generate better operational efficiency, cost effectiveness and higher processes quality [38]. Six Sigma methodology can be effectively applied in clinical areas such as infection control, medication delivery, medication administration, and laboratory processing [38,39]. On the other hand, Six Sigma implementation in service industries generally and in healthcare especially faces many challenges such as difficulties with service metrics identification, difficulty of cultural change and lack of leadership management, and the absence or difficulty to obtain the baseline data on process performance [38,39]. Despite these obstacles, the researchers exploit Six Sigma methodology in healthcare systems and the first healthcare organization to implement Six Sigma into its culture is the Commonwealth Health Corp (CHC). CHC has achieved improvements that exceed 1.2 million USD, improved the radiology throughput by 33% and decreased the cost per radiology procedure by 21.5% [40].

Heuvel et al. (2005) [41] discussed the results of Six Sigma methodology implementation at the Red Cross Hospital in Netherlands [40], where the team was able to shorten the PLOS, minimize the use of materials and devices, optimize the use of available capacities, reduce the amount of staff, and improve the cash flow. Additional benefits were also recorded, which included shorter waiting lists, elimination of unnecessary examinations, reduction in the number of defects and complications, and improvement of the output of the care process.

Mandahawi et al. (2010) [42] used the Design for Six Sigma methodology to develop a triage process for an ED at a Jordanian hospital. Different performance measures, such as length of stay and waiting time, were employed to assess the performance of the hospital's ED. The ProModel software was used to simulate the system and assess the benefits of the triage process redesign. The results indicated that after the triage system was implemented, the PLOS and the waiting time were reduced by 34% and 61%, respectively. Moreover, the PLOS and the waiting time sigma levels were improved from 0.58 to 3.09 and from 0.66 to 5.18, respectively.

2.3. Healthcare in Egypt

The Egyptian healthcare system is struggling to respond to the increasing patient numbers, while the dedicated resources to healthcare are very limited. Public hospitals are limited compared to patient load. Statistics in 2015 show that there are on average 1.57 beds and 5.75 physicians in public hospitals for every 1000 patients [43]. The Egyptian healthcare system faces many challenges including (1) Low financial support: approximately 5.2% of the total state budget in the fiscal year 2015–2016 [43]. (2) The over crowdedness of public hospitals. According to the official records, Egypt has a total number of 660 public and 1002 private hospitals serving a total population of around 91 million [43], which generates a massive patient load and endless queues of patients who always wait long hours for their consultation. (3) According to the World Health Organization (WHO), the available nurses are not just low in numbers, but they are poorly qualified, where the total number of trained nurses were just 300,000 in 2011 [44]. (4) Egyptian doctors are underpaid and often resort to debatable external means to supplement their income by seeking work in private institutions alongside their work in public hospitals or work abroad, which leads to serious complaints about the limited availability of medical specialists in state hospitals and clinics.

Recent studies revealed the lack of research that investigates the service quality provided by Egyptian hospitals. Mostafa (2005) [45] investigated the patients' perceptions and expectations of the service quality provided by public and private hospitals in Egypt, which is essential to understand the relationship between quality of care and the utilization of health services. He exhibited that no previous studies have focused on measuring and managing hospitals' service quality in the Arab world, and Egypt is no exception. He found that patients of public Egyptian hospitals are less satisfied than patients of private ones, in which he justified that the private hospitals earn profit through aggressive marketing and pricing strategies.

Zineldin (2006) [46] examined the major factors influencing patients' perception of overall satisfaction and addressed the question whether patients in Egypt and Jordan evaluate quality of health care similarly or differently, in public, semi-public, and private hospitals. He expanded technical-functional and SERVQUAL quality models into framework of five quality dimensions (5Qs); quality of object, quality of processes, quality of infrastructure, quality of interaction, and quality of atmosphere. He found that; the quality dimensions in the private hospital have an average value and the patients there are the most satisfied, while, public and semi-public hospitals have below average value for the investigated quality dimensions and the majority of the patients in these hospitals are not satisfied with the offered services.

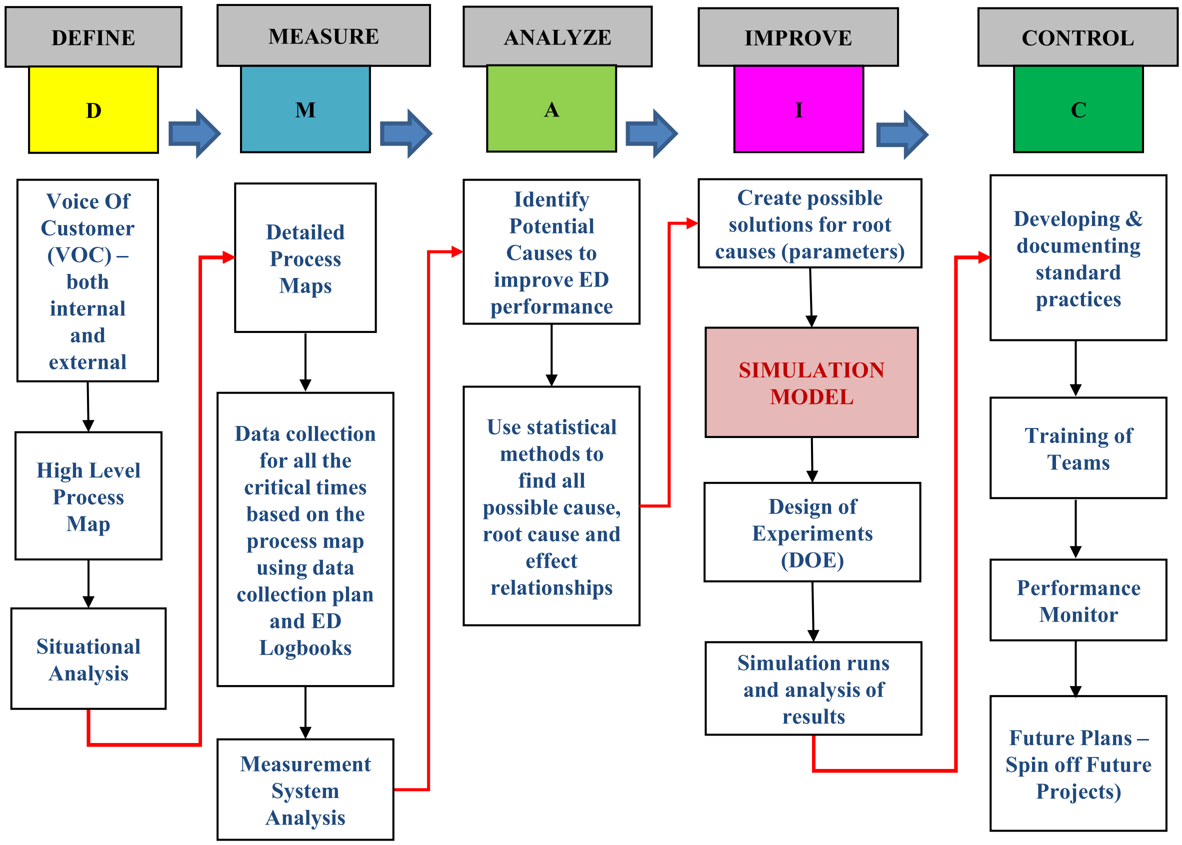

Fig. 1. Integrated Six Sigma-simulation approach.

3. Integrated approach

Many studies have applied quality improvement techniques in healthcare and EDs around the world; however, such studies are lacking in Egypt. Given the unique characteristics of the healthcare industry in Egypt as a developing country, the application of quality improvement techniques need to be investigated in order to assess and promote their benefits. This paper provides a first attempt to such an investigation by applying the Six Sigma methodology to an Egyptian tertiary private hospital. In addition to that, the DES is integrated within the Six Sigma methodology to provide a prognosis for the expected performance under the improvement scenarios, which helps in avoiding the troubles and costs that may be associated with real system modifications. This is not the first attempt to utilize such an integration in the improvement of EDs performance as similar applications can be found in [19,42]. Roberts et al. (2005) [19] used the Six Sigma methodology and Simulation to improve ED performance in the Central Texas Medical Center through improving the registration and the triage processes and developed extra resupply areas and applying 5S technique within them. Mandahawi et al. (2010) [42] applied a similar approach in redesigning the triage process of a local Jordanian hospital with the objectives of reducing PLOS and waiting time. In the current application, we focus on the influence of modifying the available medical equipment and/or replacing it with a modern medical technology. Such an issue was not considered earlier to the best of the authors' knowledge. For the improvement evaluation, we consider the medical equipment utilization as a new ED performance measure along with NEDOCS and PLOS.

As seen in the previous section, numerous researchers have conducted studies based on simulation to improve the performance of EDs. In those studies, simulation is used as a tool for evaluating the benefits that can be gained from suggested modifications off-line. However, there is no systematic method for formulating system modifications. Similar to [19,42], this research integrates Six Sigma methodology with simulation to analyze and resolve the ED overcrowding problem.

Six Sigma provides a systematic way of identifying system redesigns that can effectively enhance the performance of EDs. Based on the outcomes of the *Define*, *Measure* and *Analyze* phases of Six Sigma, system modifications are formulated in the *Improve* phase and a simulation model is constructed to quantify their benefits. Design of experiments (DOE) is used to guide simulation runs by selecting appropriate levels of system parameters in accordance with the proposed system redesigns. Designed simulation runs are carried out and their results are analyzed to study the effect of the considered system redesigns on the performance of ED. A layout of the proposed scheme is illustrated in Fig. 1.

4. Case study

The case study is conducted in a private tertiary hospital located in Cairo, Egypt with capacity of 150 beds and it serves around 20 000 ED patients annually. The ED is equipped to handle most medical situations, from acute emergencies such as heart attacks to other urgent illnesses and injuries in order to offer high-quality medical services around the clock. The layout sketch of the ED is shown in Fig. 2. The ultimate objective of the case study is to reduce the ED overcrowding by improving the ED performance measures. The average NEDOCS score for the ED during the day shift was 105, which implies that the ED is overcrowded according to the NEDOCS categories (Level 4: Overcrowded ($100 \leq$ NEDOCS < 140) [1]. Hence, this ED is an adequate pilot to test our proposed approach and to help the hospital management to take the right

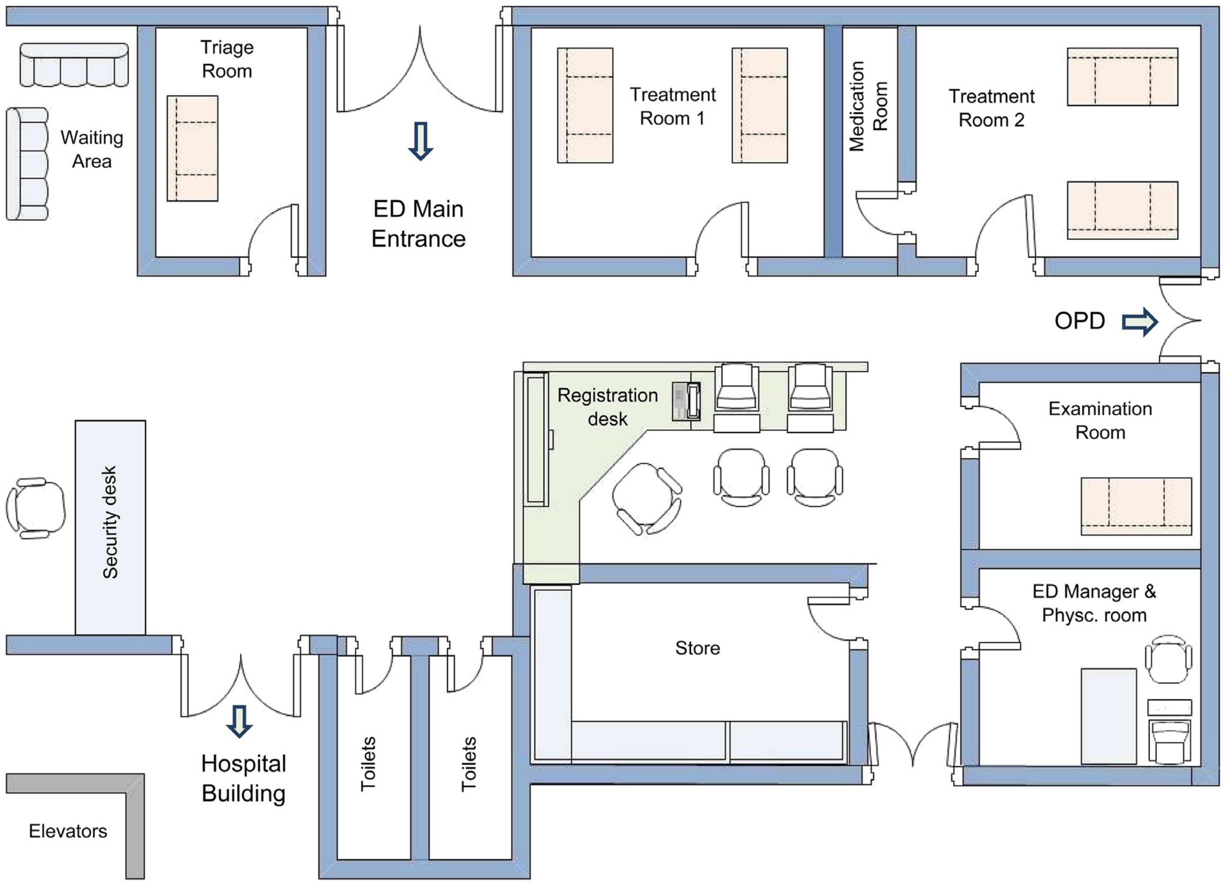

Fig. 2. Layout of the emergency department in the case study.

decisions in order to improve the patient's satisfaction through improving the ED processes.

According to the hospital's historical data, the patients arrive at the ED in various modes; approximately 80% of the patients arrive walking-in, 10% arrive in ambulance, and the remaining 10% arrive on wheel chair. Patients who arrive in ambulance are immediately admitted to a bed upon their arrival. However, ambulatory patients can first go through the triage process, if their medical condition is not critical. The distribution of triage categories for the walk-in patients was found to be 65% non-urgent, 33% urgent, and only 2% emergent. Moreover, approximately 80% of the patients admitted to ED require radiology services, among which 75% require a service from the diagnostic imaging area.

As shown in Fig. 3, all arriving emergency patients to the ED are first escorted to the triage room to be classified into one of three categories (emergent patients, urgent patients, and non-urgent patients). A physician attends the patient after the triage process. Based on the patient prognosis, the physician administrates the required clinical tests, such as radiology and/or laboratory tests. Patients, who do not need any clinical tests, are given the necessary medication and discharged after their condition is stabilized. When clinical tests are requested, the physician awaits for the results of such tests to take further actions.

The walk-in patient is registered at the registration desk at the bedside if he is admitted to the bed upon arrival, where the registration clerk collects all the personal data. After that, the patient is admitted directly to bed in case of bed availability, otherwise, the patient awaits in the waiting area for the examination room. The procedure to admit a patient to the ED bed varies by the category of the patient and the arrival mode. Patients who arrived in an ambulance and assigned emergency status are directly placed in an examination room but in some non-urgent cases they go through the usual procedure discussed earlier. Typically, an ED nurse comes to the waiting area to transfer and admit the patient to a bed then assists to insert cannula, patient identification band, collect clinical test results (i.e., withdraw laboratory tests). After the initial evaluation, the physician may order ancillary tests, such as laboratory or radiology tests. After the examination of a patient, an ED physician would decide whether the condition of that patient needs a radiology service, which can be done in one of the four sections of the main medical imaging department that is equipped with two X-ray rooms, one Computerized Tomography Scan (CT-Scan) room, one Magnetic Resonance Imaging (MRI) machine, and one Doppler and/or Duplex Ultra Sound (US) machine, which is located at the second floor of the hospital.

The ED physician, in some cases, consults the specialty physician, whom revises the patient complaint and prescribes any extra needed medications or asks for extra laboratory and/or radiology tests. After the test results are returned to the physician, a decision regarding the disposition of the patient is then made depending on his condition. In case the patient requires further treatment, he would be transferred to the inpatient unit. While, he would be discharged out of the ED, if his condition is stable and no further treatment is required

5. Implementation of the integrated approach

In this section, the implementation steps of the Six Sigma and simulation integration will be explicitly explained and the results of the analysis of the case study application will be discussed.

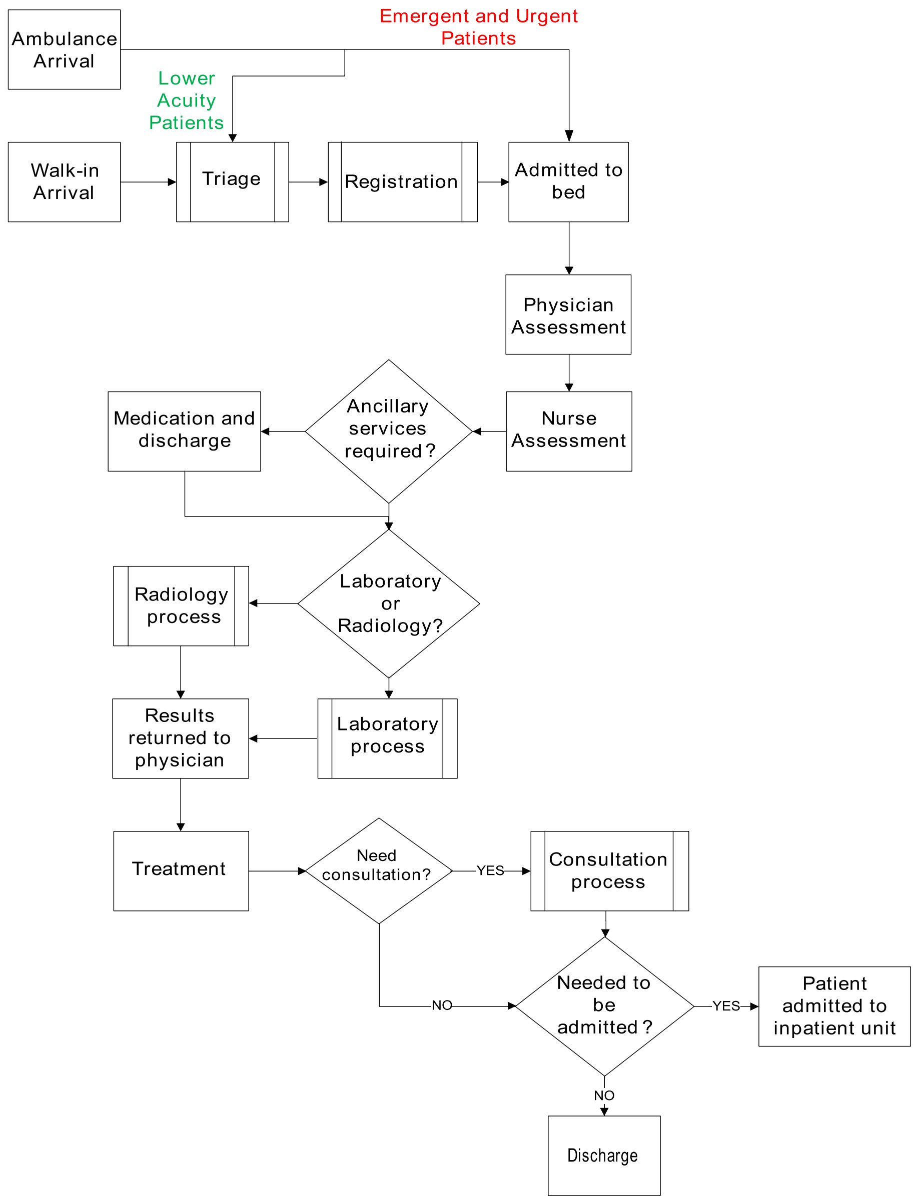

Fig. 3. The workflow of ED processes.

5.1. *Define phase*

5.1.1. *NEDOCS level of the ED*

The original crowdedness level of the ED has been calculated according to the NEDOCS in order to identify the extent of the crowding problem, by applying Eq. (1) over the collected data. Fig. 4 reports the computed NEDOCS score during the day shift (from 8:00 AM to 5:00 PM), which has an average value of 105. This implies that the ED is Level 4: overcrowded ($100 \leq$ NEDOCS $<$ 140).

5.1.2. *Voice of the customer (VOC)*

The main objective of surveying the voice of the customer (VOC) is to identify and characterize the measures and indicators used to document the ED overcrowding problem and to identify the level of consensus among a group of ED staff on the importance and relevance of specific measures to document ED overcrowding. The customer survey was used to collect information about the ED overcrowding problem and its possible causes. Conjointly, it helped to collect the opinions of the ED staff (internal customer) about the extent of the problem and its associated factors.

The Asplin model [47,48] was used to describe the characteristics of these measures in terms of the input–throughput–output model, and to report on the purposes of their use in the context of a research on ED overcrowding, so that the collected information can be better used to allocate the most crowded areas as well as the most influencing causes. From the literature, a list of potential indicators of overcrowding and their operational definitions was generated and provided within the survey questionnaire. The survey questioned the demographics of the regional population, type of hospitals, annual census, and bed capacity, as well as all the possible factors that could influence the overcrowding to any degree and the time intervals that experienced the worst episodes of overcrowding. Putative causes of overcrowding were provided, and respondents ranked these causes on a 5-point scale: scale 1 indicates not a cause, scale 3 indicates somewhat of a cause, and scale 5 indicates a major cause. Respondents were also asked about the duration of the overcrowding problem and their impressions about its effects on the patients present in the ED, such as delayed

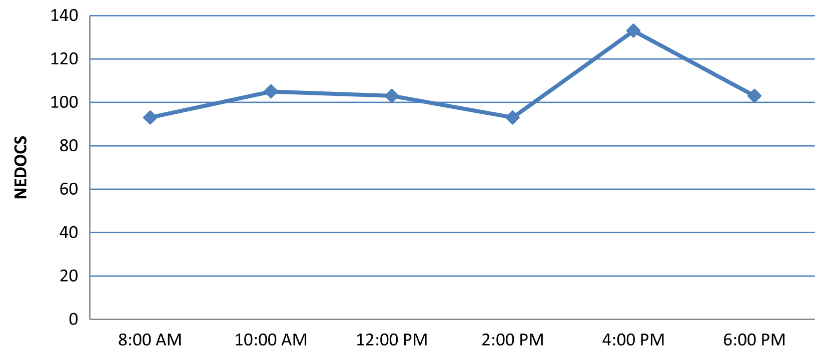

Fig. 4. The NEDOCS score of the emergency department during the day shift.

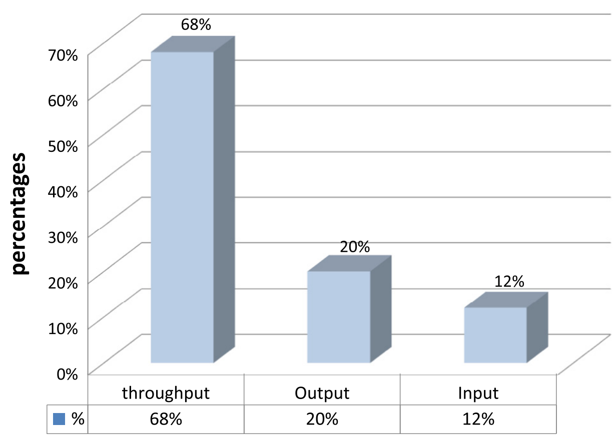

Fig. 5. Survey results according to input–throughput–output model.

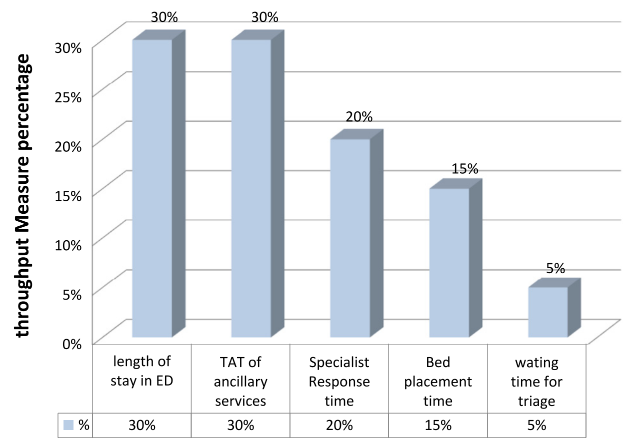

Fig. 6. Throughput measure survey results.

diagnosis and treatment and the increased risk to achieve poor outcomes. The survey was pre-tested on a convenience sample of 15 ED physicians, 12 ED nurses, and 5 administrative staff.

The survey data were analyzed according to the input–throughput–output model [47], then the Pareto chart was used to identify the top parameters related to ED overcrowding. Throughput parameters such as (triage, room placement, testing, ED treatment, and the initial provider evaluation) were most commonly used to document ED overcrowding (68%), followed by output parameters (20%) such as (disposition of ED patients), and input parameters (12%) such as (emergency care, unscheduled urgent care, and safety net care) as reported in Fig. 5.

Because the throughput parameters are highly related to the overcrowding problem, their causes were thoroughly investigated and analyzed. The results indicated that PLOS affects by (30%) on the problem, turnaround time (TAT) for ancillary services (30%), specialist response time (20%), bed placement time (15%) and waiting time for triage (5%) as shown in Fig. 6.

5.1.3. *Process mapping*

Fig. 3 shows the currently implemented process map within the study case hospital, which reports the different process steps for the ED patients; the sequence and logical connections were afforested in Section 4.

5.2. *Measure phase*

In the *Measure* phase, the hospital historical data related to the main causes of the overcrowding problem, such as the PLOS and TAT of ancillary services, were collected in order to identify, determine, and correlate various factors that influence the ED overcrowding because resolving them would overcome the majority of the problem. The ED logs data of the day shift that extended from 8:00 AM to 5:00 PM, for a period of four months, September to December 2012, were extracted from the hospital information system. This period represents the time interval during which, the highest patient arrival rates occur with high NEDOCS level.

In order to perform the necessary analyses and simulation, four kinds of data were exploited: the arrival rates of patients, the logical connections between the activities of the different scenarios occurring in the ED, the population characteristics, and last but not least, the durations of each single activity taking place in ED.

5.3. *Analyze phase*

In the *Analyze* phase, we inspected the causes of the problem such as the patient flow, triage categories, and Takt time (TT), and their effects on the ED performance as explained in the sequent.

5.3.1. *Arrival rate/patient flow analysis*

From the data extracted during the *Measure* phase, the patients arrive in various modes at the ED, specifically 8% of the total arrivals are walk-in while ambulance or on wheel chair arrivals represent a minor percentage of 10%, each. By best fitting data, the arrival process can be expressed as a Poisson process of a constant and uniform arrival rate of 2.4 patients per hour.

5.3.2. *Triage categories analysis*

The care delivery process and the service time vary based on the triage category of the patient. For example, emergent patients are typically admitted to a bed immediately upon their arrival, whereas, non-urgent patients experience a delay most of the time. Hence, the knowledge of the probability of a patient to be classified as a non-urgent, urgent or an emergent is essential for the simulation modeling. The distribution of the triage categories indicated that 98% of the walk-in patients belong to the urgent and non-urgent classes and the most of them face a long waiting time, while the emergent patients only represent 2% of the walk-in patients and 5% of the total arriving patients (ambulance, walk-in, and wheelchair patients). Hence, the study focuses on urgent and non-urgent patients disregarding the emergent patients (interested reader can find more information on the effect of the emergent patients on the delay in service for non-emergent patients in ED in [49]).

5.3.3. Takt time analysis

The Takt time is an indicator used to define the maximum allowable time to serve each patient per single process. It is based on the average arrival rate of patients. For an arrival rate of 2.4 patients per hour, the TT is found to be 25 min. The average turnaround time (TAT) for each major process is then evaluated and compared to the TT. It is found that the average TAT of the radiological service process is more than the double of the TT, which denotes that this process is the core cause for patient waiting and consequently the high PLOS. Another reason is that approximately 80% of the ED admitted patients require a radiology service, among which 75% require a service from the diagnostic imaging area.

The radiology department renders its services to outpatients, inpatients, ambulatory patients, and patients from the ED. A Pareto analysis is utilized to determine the main reasons and the frequency of the different types of radiological services delivered to ED patients. It is found that the major types of radiological services requested are X-ray and Ultrasound (US) Imaging.

The radiology department has two X-ray rooms (i.e., two X-ray machines): one operates under analog technology while the other is digital. Detailed analysis of the X-ray and US services is conducted to determine the elements that cause much of the delay. In order to study the effect of an imaging session on the TAT of a patient who needs the X-ray service, a regression model was formulated twice: one for the analog X-ray machine (Eq. (1)) and another for the digital one (Eq. (2)). The assumptions used to validate the regression model are met (e.g., normality and constant variance) for both the analog and the digital X-ray machines. The Mood's median test is used to examine if there are any statistical discrepancies between the imaging session done using the different X-ray machines and the operator/technician performing such imaging sessions. It is found that there are noticeable statistical differences between the imaging sessions performed using both machines, on the contrary, the operational duration by the different technicians are almost identical.

$$\begin{aligned} \mathrm{TAT}_{XAnalog} = {} & 9.82 + 0.985(\text{request registration time}) \\ & + 0.931(\text{imaging time}) \\ & + 1.13(\text{film formation time}) \\ & + 1.31(\text{report formation time}) \end{aligned} \tag{2}$$

$$\begin{aligned} \mathrm{TAT}_{XDigital} = {} & 8.44 + 1.04(\text{request registration time}) \\ & + 0.701(\text{imaging time}) \\ & + 1.12(\text{film formation time}) \\ & + 1.16(\text{report formation time}). \end{aligned} \tag{3}$$

The Linear regression models—Eqs. (2) and (3), show that the imaging time coefficient is significantly higher in analog compared to digital X-ray. The higher value of $\mathrm{TAT}_{XAnalog}$ implies the long time taken by the analog X-ray to serve a patient and this leads to serving fewer number of patients than the supposed number according to the TT. This situation consequently leads to long waiting time and high PLOS. Hence, improving this service with faster equipment would result in higher number of served patients, lower PLOS, and more satisfied patients.

5.4. Simulation model development

The Six Sigma's *Define, Measure and Analyze* phases provide most of the basic data needed to construct the simulation model. In addition, based on the best fitting curves of the historical data, appropriate probability distribution functions were assigned to each stochastic input parameter utilizing the Goodness of Fit test (Pearson's chi-squared test). All the probability distribution functions have a P-value greater than 0.05.

Table 1 lists the fitted probability distribution functions for the simulation model based on historical data; where EXPO(λ) is the exponential distribution function, TRIA(α, β, γ) is the triangular distribution function, UNIF(a, b) is the uniform or rectangular distribution function, LOGNORM(μ, σ) is the log normal distribution function, and $\lambda, \alpha, \beta, \gamma, a, b, \mu$, and σ are respectively the exponential rate of change, the start of the triangular interval, the mode, the end of the triangular interval, the start of the rectangular interval, the end of the rectangular interval, mean, and standard variation of the normal distribution parameters.

The number of patients and their percentages in each activity is essential for constructing the simulation model. Spreadsheets of actual data from ED were collected. This data consisted of the number of patients who entered the ED and their division in each department for four months during day shift from 8 a.m. to 5 p.m. the resources distribution used and patient disposition per triage category/level were calculated. Approximately 82% of the patients are registered as ED patients while the rest are considered as outpatient department (OPD) patients who do not stay overnight.

Several details in the ED process are considered minor as they do not affect the overall performance. Therefore, minor details can be neglected by adopting some assumptions that are necessary to reduce the sophistication level of the model. In the current study, the following assumptions were adopted.

- All arrivals were categorized as walk-in arrivals as it is the major arrival type as mentioned in Section 4.
- The flow of the patients classified as triage level 1 (emergent) was not considered because they represent less than 5% of the total patient flow and they are immediately admitted to a bed upon arrival.
- The patient would occupy the bed until discharged.
- All transfer times in the ED were neglected.
- All staff resources and treatment area are available 100% of the time. No break-time is built into the model.
- No statistical difference between all the weekdays.
- Each patient retains a single classification throughout his/her stay in the emergency room.
- ED Patients remain in one treatment area from admittance to discharge.

The simulation model was constructed using SIMUL8 software [21] based on the understanding gained through the process mapping of the actual system. In the simulation model, patients arrival is generated according to the distributions fed into the model. Upon arrival, the patient would be assigned a triage category and an ailment based on the probability distributions of both conditions. In this stage, a priority level is given to the patient, and then the patient is directed to the triage process. Then, the ED physician decides if the patient is ED case or not. Non-ED cases are directed to OPD. After the allocation of a bed, a treatment time is assigned to the patient according to the type of investigation ordered by the ED physician. The treatment time is a function of

Table 1
Probability distribution functions for ED processes in the case study.

Task	Time distribution
Interarrival	EXPO(25)
Triage	TRIA(5,8,15)
Registration	UNIF(10,15)
Nurse assessment	UNIF(5,10)
Physician assessment	EXPO(4)
Medication conducted	TRIA(10,15,20)
Patient transfer	TRIA(5,6,7)
Sample transfer	TRIA(2,3,5)
Lab analysis	TRIA(20,25,30)
X-ray digital imaging session	TRIA(2,5,16)
X-ray analog imaging session	TRIA(5,8,17)
US imaging session	TRIA(5,8,17)
Film formation	LOGNORM(8,10)
X-ray report formation	EXPO(5)
US report formation	EXPO(13)
Consultant response according to 3 specialties	TRIA(10,15,20), TRIA(5,10,15), TRIA(10,15,20)
Consultant assessment	EXPO(5)
Discharge time	TRIA(30,45,60)
Admission time	TRIA(20,30,40)
Paper work	UNIF(3,5)

the type of ailment and severity of the condition. After treatment ED physician decides which patient is hospitalized or discharged.

The simulation was run for several times to determine the warm-up period. Warm up period defines the length of time which is allowed to elapse before the gathering of statistics is started. Warm-up period is necessary to eliminate any bias due to observations taken during the transient state of the simulation run. The period after which the patient turnaround time appeared to be stabilized to give consistent values was considered as warm-up period. Subsequently, a warm-up period of 4 days was estimated. The results were collected after 30 replications of the model with 20 days as replication length. The number of replications is determined based on the sequential procedure described in [50] with a confidence level of 95% and a relative error less than 0.15. Meanwhile, the replication length of 20 is arbitrarily selected to make sure that the simulation output remains in its steady state for sufficiently long period of time.

The verification of the model is an important step that needs to be done, once the development of the model is complete. It is required to determine the correctness of the logic and the accuracy of the flow of entities, which can be fulfilled using many ways, such as:

- Using the tracing option in the software.
- Checking the internal logic of the modules of the model.
- Using visual animation.
- Comparing the model output for a deterministic case with the information obtained from a manual simulation using the same data.
- Input parameters were changed to check if the results changed accordingly.
- Performing interviews and face-to face discussions with the appropriate personnel in order to assess the accuracy of the logic.

In the current application, several interviews were performed with the appropriate personnel to verify the case study simulation model. The validation of the model which follows the verification step is a very important step to prove that the model is a close representation of the real system. Here, the model was validated by comparing the simulation performance results with the actual historical records of the case study, in terms of the mean and the standard deviation of the PLOS as reported in Table 2. Kruskal–Wallis test is used to ascertain the differences between the simulation model and the actual system. The hypothesis test at 95% confidence interval illustrated that the results from the simulation model and the actual observations are statistically comparable observations and accurately reflect the real system.

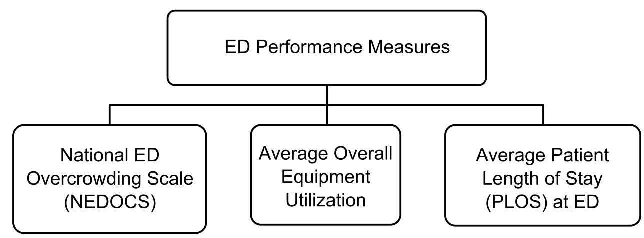

Fig. 7. Performance measures.

5.5. Simulation results and analysis

The performance measures considered in this study are outlined in Fig. 7. The NEDOCS is commonly used in health care industry [1] to measure overcrowding in EDs, where higher values of NEDOCS indicate higher congestion level. The PLOS is a key factor to measure the quality of care as well as the patient satisfaction. Equipment utilization defined as the ratio between the total time that the equipment has been used to serve patients to the total availability time. Despite being a very important performance measure, equipment utilization has not received much attention in literature.

As shown earlier in the TT and TAT analyses, the radiological service represents a major bottleneck of the ED processes. Therefore, the main focus of the process redesign suggestions is to improve this element, which can be done by considering two options related to the type of the radiology equipment technology: 1—introducing a Picture Archiving and Communication System (PACS) and 2—replacing the current analog X-ray machine with a digital one. PACS replaces the X-ray film with digital images and consequently, it facilitates images viewing and reporting. The analysis provided in Section 5.3 shows clearly that the overall time needed by the digital X-ray is lower than the time required by the analog one. Therefore, both options will help to reduce the time needed for the complete the radiological analysis task. At this stage, the role of the experimental design is to study the effects of all the possible combinations of these two options on the ED performance.

The DOE considers four different scenarios by manipulating two factors with two levels, each. Table 3 provides the details of the two levels used for each factor and how these levels are realized in the simulation model. Five replications are executed for each combination of experimental setting with a replication length of 1200 days. Different random number seeds were used

Table 2
Comparison between simulation and historical data result.

	Simulation model PLOS [min]	Historical data PLOS [min]	Kruskal–Wallis test result
Mean	112	118	$P > 0.05$
Standard deviation	57	63	

Table 3
Factors and values for each factor level.

Factor	Levels		Realization method
	Low (L)	High (H)	
PACS integration	No PACS	PACS	By removing the film processing and report formulation times.
X-ray replacement	As-Is (Analog)	Replace with digital	By controlling the examination time of X-ray equipment.

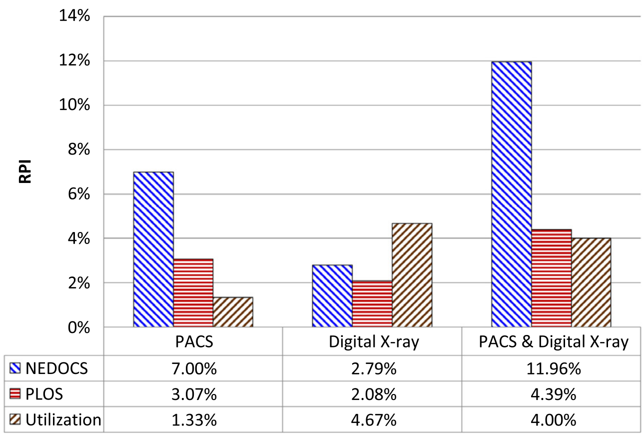

Fig. 8. Relative percentage improvement results.

to overcome the correlation between the different cells of the factorial experiment. The system was found to stabilize after 20 simulated days, therefore the observations of the first 20 days are discarded in order to remove the effect of the start-up condition, which is an idle and empty state. The output of the remaining days is used to evaluate the performance measures.

In order to investigate the performance of the four proposed scenarios versus the current As-Is situation (i.e. no use of PACS and X-ray machines), the relative percentage improvement (RPI) is computed as the differences between the average performance measure of the current situation and the average performance measure obtained by the proposed new scenario divided by the former and multiplied by 100, for each performance measure.

The average performance measures are evaluated for the five conducted replications of each scenario. A positive RPI indicates an improvement over the baseline scenario, except for the equipment utilization measure. Fig. 8 shows the RPI results for the considered three performance measures.

Based on the obtained results, proper action plans are generated in order to improve the performance of the ED up to a target level. It is evident that integrating PACS with the replacement of the analog X-ray machine by a digital one produces the highest impact in terms of both NEDOCS and PLOS. Meanwhile, the average overall equipment utilization will only be reduced by 4% immediately after introducing the PACS to the system.

The option of just replacing the current analog X-ray machine with a digital one produces the lowest improvement level to both NEDOCS and PLOS. These results were summarized and presented to the decision maker in order to authorize the appropriate actions. The Six Sigma DMAIC cycle continues to monitor the performance under the implemented system modifications and accordingly, future improvement projects are planned as another turn of the DMAIC cycle starts again at the *Define* phase.

6. Conclusion

This paper integrated the Six Sigma methodology with the DES to provide a systematic approach for solving the overcrowding problem in EDs. Six Sigma methodology is first applied to determine the reasons behind the ED overcrowding using its well-known DMAIC cycle. Thereafter, the DES and DOE are used within the *Improve* phase in order to study the effects of the different improvement scenarios on the overcrowding measures as well as the medical equipment utilization.

A case study was presented to demonstrate the proposed approach. In the *Define* phase, face-to-face interviews were made with ED staff in order to verify the process flow, waiting times, activity durations, and available resources. In addition, a survey has been carried out in order to identify the reasons behind the ED overcrowding problem. In the *Measure* phase, data were collected from the hospital historical database then the measurement system analysis was applied to assess the collected data. In the *Analyze* phase, the data were inspected to determine the causes of the ED overcrowding.

After extensive analyses of the current ED operations, the potential areas for the improvement were identified. The analyses showed that the technology of the X-ray machine has the major impact on the ED performance. Accordingly, two resolutions are proposed: introduce a PACS system and replace the existing analog X-ray machine with a new digital one. The DES was then used to assess the performance of the system subjected to different combinations of the proposed resolutions.

The simulation model was verified and validated using the conducted interviews and the historical data. The results proved the accuracy of the model to closely represent the current ED system. Afterwards, the DOE was used to prepare simulation experiments with different scenarios. Then, the NEDOCS, PLOS, and the overall average medical equipment utilization measures were used to assess the ED performance.

The results showed that the implementation of the PACS and the replacement of the current analog X-ray machine together would achieve the best results, which surpass the improvement obtained by solely implementing the PACS. These results were reported to the management authority in order to take the appropriate actions. After implementing the best solution in the real system and checking that the desired effects are met, the *Control* phase then comes into action to ensure that the ED processes do not slip back to uncontrolled state.

To the best of our knowledge, there is a lack of previous studies that investigate the effect of medical equipment utilization on ED performance. This research followed a systematic procedure to improve the quality of service at the ED and to study the effect of medical equipment technology and availability on ED performance during overcrowding.

The presented integrated Six Sigma-Simulation approach has proven to be versatile in providing guidelines and developing and assessing different improvement scenarios. It provides a more systematic improvement methodology instead of relying on the personal intuition and judgment in proposing improvement scenarios and assessing their results via disentangled simulation experiments. Such an approach can be also utilized to improve the performance of other healthcare management systems, especially in developing countries, by exploiting its potential for substantially improving and developing healthcare services, in particular when considering its low investment cost. We recommend to extend the current research to study ED overcrowding in Egyptian public hospitals as they endure higher overcrowding levels and bear lack of advanced medical equipment.

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