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Leveraging discrete event simulation modeling to evaluate design and process improvements of an emergency department

Zahra Zamani*

Abstract

This study exemplifies the practical application of the Discrete Event Simulation (DES) approach for evaluating the effectiveness of suggested processes and design modifications in improving the existing bottlenecks of an Emergency Department. EDs are under escalating pressure to deliver efficient care while handling considerable challenges, such as overcrowding, delays, length of stay, safety risks, or staffing. Many ED appointments are non-urgent and can be treated in an alternative outpatient setting. Suitable demand-capacity matching and adjusted admission protocols reduce ED patients' Length of Stay (LOS) and improve boarding times. Alternatively, new design suggestions include applying results-pending areas where lower acuity patients wait for their pending lab or imaging results. In this study, DES assesses underlying conditions and existing bottlenecks in an existing ED. The current ED flow involved a "pull-until-full" for exam room boarding and bedside registration after triage fulfillment. Nonetheless, the ED experienced boarding delays for patients waiting to be admitted into the hospital. This study explored two scenarios in DES as potential alternatives for reducing LOS: the implication of a "rapid-admit" protocol and a "results-pending" area. Findings showed that the Rapid-Admit process reduced the admitted patient's LOS by 16%. On average, the results-pending implication reduced the admit LOS by an average of 32% across all ESI levels. These findings suggest the importance of process, staffing, and spatial modifications to achieve ED operational improvements. DES enabled a data-driven approach to evaluate bottlenecks, enhance architect-owner communication, and optimize the system for future design and process improvement alternatives.

Keywords: emergency department, discrete event simulation model, length of stay, rapid admission, results pending area, technology integration

1. Introduction

ED crowding, unpredictable arrival rates, evolution in the appeal for ED services, workload variability, and resource limitations are obstacles to improving ED flow (Srinivas et al., 2021). Across the United States, ED crowding remains the central issue in the healthcare system as it provides mainly half of the delivered medical care (Trzeciak & Rivers, 2003). In the last 20 years, Many Eds have been operating at overcapacity with an increase in demand by 50%, while Eds are continuously short-staffed, and the number of ED units has declined by 11% (American Hospital Association, 2015).

Crowded EDs reduce staff satisfaction and productivity and the increased likelihood of experiencing burnout or suicide (Schernhammer & Colditz, 2004; Wiler et al., 2011). Further, ED overcrowding diverts valuable staff resources from other patients, reduces ED capacity and patient

*Senior Design Researcher and Healthcare Planner, BSA LifeStructures, USA, zzamani@bsalifestructures.com
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mortality, and causes a loss of revenue (Boulain et al., 2020; Quinn et al., 2007; Yancer et al., 2006). At the treatment stage, resource shortages (staffing, ED rooms, imaging rooms) and delayed test results (Ultrasound, X-Ray, computed tomography (CT scan) become the bottleneck that causes ED congestion (van der Linden et al., 2017). Several studies have focused on identifying the source of ED crowding at the treatment and discharge stages (Amarasingham et al., 2010; Patel et al., 2014; Singer et al., 2011; van der Linden et al., 2017).

Growing evidence has demonstrated an association between long ED boarding times and adverse events, such as in-hospital deaths and crowding (Amarasingham et al., 2010; Boulain et al., 2020; Patel et al., 2014; Singer et al., 2011). For instance, Boulain et al. (2020) found that among 68632 ED visits, patients with boarding times more extended than four hours were more likely to experience hospital deaths. The delayed discharge process to transfer or admit patients from Eds to inpatient beds also plays a prominent role in ED waiting times. Several studies have examined different strategies to reduce undesirable ED crowding. These techniques include directing low-acuity patients to a co-located outpatient facility, public education, or increasing the working hours of primary care centers (Dolton & Pathania, 2016; Morley et al., 2018; Sharma & Inder, 2011). Other investigations have focused on expediting the patient flow within the ED system (Amarasingham et al., 2010; Bal et al., 2017; Copeland & Gray, 2015; Han et al., 2010; Valipoor et al., 2021a).

Established in 2005, the Rapid-Admission policy (RAD) enables admitting physicians to evaluate and request patient boarding before fulfilling all diagnostic tests (Amarasingham et al., 2010; Quinn et al., 2007). This intervention reduces Length of Stay (LOS), boarding times, and admission orders (Amarasingham et al., 2010; Quinn et al., 2007). Another approach for lessening ED LOS is directing low-acuity patients to an ED internal waiting area termed "Results-Pending" as they anticipate imaging or lab results (Bryant, 2013; White et al., 2014; Zilm et al., 2010). Together with other interventions, these studies show that applying the results-pending area correlated to improved efficiency and reduced LOS outcomes.

Discrete Event Simulation (DES) represents the operation of a system as a discrete order of events in time. Events happen at a specific time and exhibit a state transformation in the system (Page & Kreutzer, 2006; Zeigler et al., 2000). Simulation contributes to studying the behavior and interactions within a system to facilitate decision-making, productivity, and promptly experimenting with new potential possibilities (Mielczarek & Uziałko-Mydlikowska, 2012; Norouzzadeh et al., 2014; Srinivas et al., 2021; Swan et al., 2019). Fundamental elements of DES in healthcare include patient flows through the system, arrival rates, location resources, equipment resources, staffing resources, and service time (Cai & Jai, 2019).

Health research from 1981 onwards has applied DES to improve healthcare systems and operations by evaluating effective resource utilization (Mielczarek & Uziałko-Mydlikowska, 2012; Swan et al., 2019). Healthcare systems employ DES to acquire data on the system's current state, experiment with different control measures, and decide on the most suitable strategy (Martin et al., 2003). Applications include re-engineering patient flow for reduced waiting time or improving staff scheduling (Mielczarek & Uziałko-Mydlikowska, 2012; Swain, 2011). DES studies pursue resource allocation optimization by creating a future forecast for the quantity or adjacency of architectural spaces (Mielczarek & Uziałko-Mydlikowska, 2012; Oh et al., 2016; Shim & Kumar, 2010a).

For emergency departments, simulation models often explore patient flow staff activities, patient acuity, the actions performed, and performance measures (Oh et al., 2016; Quinn et al., 2007; Rossetti et al., 1999; Swan et al., 2019; Yancer et al., 2006). This scenario will respond to "what if" questions by altering patient flows, staffing resources, or built environment variables. For example, Oh et al. (2016) evaluated and compared system improvements in an ED, finding that reducing adult patient Computed Tomography (CT) scan oral contrast drinking time improved self-dictation use in radiology and reduced sample re-collection rates affecting LOS.

Shim & Kumar (2010) employed simulation studies to study ED overcrowding improvement to show that adding an extra payment station reduced patient waiting time by 41%. Valipoor et al. (2021) explored the likely impact of boarding the patients in the hallway rather than in exam rooms. Findings showed that LOS was significantly reduced for all patients, provided the EMS triage scenario implementation (a dedicated space for triaging EMS patients).

Based on the literature review, we understand that applying the simulation technique facilitates hospital services. Thus, the study aimed to explore the possibility of providing design or operational solutions using DES techniques. This way, the design team evaluated several optimized scenarios without needing scale tests.

2. Methodology

2.1 Data and Simulation Input

The site was purposefully selected for the simulation modeling as part of the architecture design process for designing a new ED construction in the sub-urban region of North Carolina (NC). Processing time, staffing schedule, and staff input for two existing EDs were provided as a benchmark for the new facility. The June 2021st quality assessment report for this facility suggested the following benchmarks to be improved: Left Without being seen = 1.87% (target goal: <0.5%); ED arrival to discharge=158 minutes (target goal 125 minutes) and ED orders for admission (request for bed) for ED departure = 214 minutes (Target: 150 minutes). Therefore, the client was interested in solutions for flow modifications or design alterations that improve patient waiting times and length of stay as a guideline for the new ED facility.

This cross-sectional case study focused on one of the client's suggested ED benchmarks. In addition to the ED, the facility also included an outpatient laboratory area providing care for both the ED and outpatient populations. The site was a stand-alone emergency department with 12 private treatment rooms, an X-ray, CT scan, ultrasound testing, and an ambulance receiving area. The staff had converted one of the office rooms into an exam room, resulting in 13 treatment rooms (Figure 1).

This study derived input and validation for this model from over 20,336 unique patient visits collected from July 1st, 2020, to June 30th2021. We collected no identifiable information from the patients for this evaluation. Each patient's information included over 24 variables, including arrival time, ESI level, process timestamps, last ED room, ED disposition, and ED departure.

Figure 1 The Emergency Department layout and room functions (Image Copyright: Author).

Patient-level visit data was available for ED, lab, and radiology subprocesses. Physicians' and nurses' schedules defined the staffing levels. Process timestamps comprised: 1- arrival to triage; 2- arrival to registration; 3- arrival to first bed; 4- arrival to the first provider; 5- arrival to first disposition selected; 6- arrival to first admit order; 7- arrival to first bed; 8- arrival to ready to discharge. Differences between timestamps were applied as processing times for registration, triage, lab specimen collection, radiology process, ED time with the provider, ED wait for BED, and ED bed assignment. Different proportions extracted from the data included acuity, final disposition, and lab or imaging orders. The model outputs, such as LOS, wait for provider, or time with the provider, were compared with the current ED benchmarks for validation purposes.

The DES was developed using several assumptions. Firstly, based on the staffing schedule, the provider is on-site when needed and not acquired by another patient. We also assumed that the model's movement characteristics and path of travel resemble the personnel's actual behavior pattern (using the shortest path of travel). Patient arrival schedule was calculated based on the maximum number of patients; 6- process data from July 2020 to June 30th, 2021; 7- ESI level 1 patient are the only ones using the trauma room. The model was simulated for six months, and the data collected for the first two days were eliminated for warmup.

The data excluded the following patient types: Expired, left-without-being seen (LWBS), left without notification, Behavioral health pending placement, and discharge-transfer refusal. These exclusions resulted in 19,839 data visits (AVG = 54, Min = 32, Max = 85, Mode= 52, SD = 9.6). The distribution of different ESI levels was calculated and accounted for in the simulation model (ESI 1 = 0.14%, ESI 2 = 8.21%, ESI3 = 54.51, ESI 4 = 34.25%; and ESI 5 = 2.9%). The model described the hourly arrival rate from 00:00 am to 12 am as a percentage per hour. The calculation revealed that 24.51% of patient arrivals happened between 6-9 pm, and the lowest volumes happened between 3- 6 am (5.64% of total daily volume). Patient disposition data were calculated as Admit = 6.85%, discharge = 91.24%, and transfer = 1.91% (admit and transfer patients were grouped for the model input). The model also considered the distribution of patients per ESI level for admission and discharge (Table 1).

Table 1 The distribution of patients per ESI level for admission or discharge dispositions.

ESI	Admit	Discharge
1	1.26	0
2	26.76	6.52
3	60.65	54.01
4	1.33	37.3
5	0	3.17

2.2 Patient Flow

Walk-in patients arrived at the ED through the front door and then completed the quick registration at the front desk. The front desk assigned an emergency Severity Index (ESI) based on a mixture of resources. This level ranges from 1 (most severe) to 5 (least severe). In this simulation model, we assumed all ESI 1 patients arrive in the ambulance and are transferred to the resuscitation room or any available exam rooms. EMS patients were given priority for staffing and room allocation. A nurse technician escorted the patients from the waiting room to assigned exam rooms for other patients. The ED employed the pull-until-full approach, where patients are escorted to any available exam rooms until there is no capacity.

In exam rooms, patients receive care through a nurse triage. Then the physician delivers an initial assessment and selects a disposition. The complete registration occurs inside the room while the patient waits for the imaging, lab, bed assignment, or discharge disposition administration. Imaging techs or nurses collected lab samples inside exam rooms. If needed, imaging techs escorted the patients to the designated radiology or CT rooms for imaging orders. In the current model, patients waited for lab or CT results in the exam room. The patient's length of stay (LOS) was measured from arrival to when the patient left the ED. Depending on ESI levels, physician or nurse time spent with patients was retrieved from historical data. After the model was completed, the researcher verified the sequence of events by communicating with the nurse managers and unit director and conducting on-site observation assessments. Figure 2 displays the overview of the simulation model 3D environment.

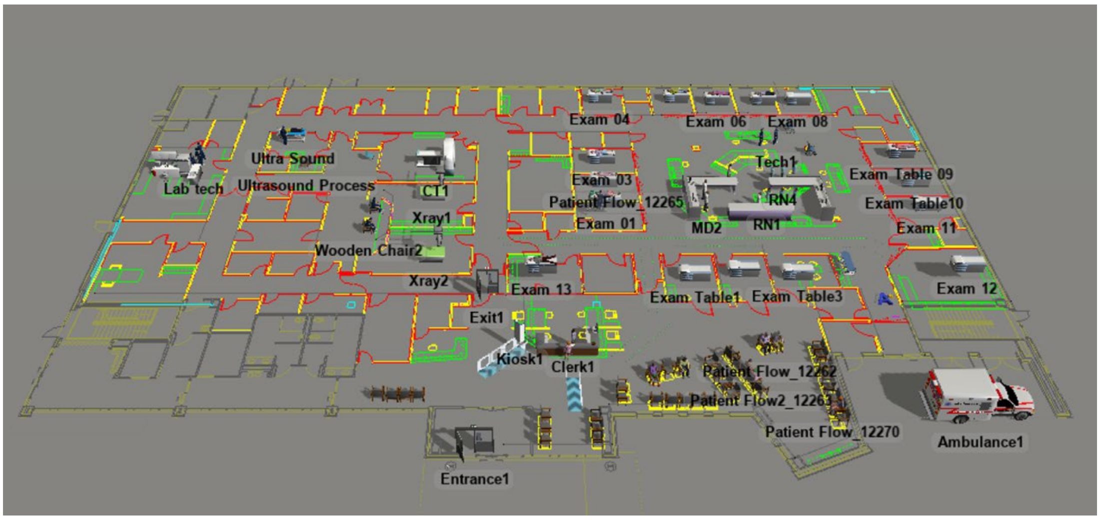

Figure 2. The 3D perspective image of the simulation modeling connects space resources with staff resources and patient flow (Image Copyright: Author).

2.3 Scenario development

The current ED performance compared to the proposed system was assessed using a DES built-in FlexSIM HC 2021. The focus was on identifying low-cost and achievable physical environment or flow strategies for improving patient flow and reducing LOS. Firstly, we explored the implementation of a rapid-admission protocol that allows the physician to request a patient bed in the inpatient unit before completing all diagnostic testing. The assumption was that this patient flow modification would decrease the LOS for admitted patients, and accordingly, with more exam rooms and clinician availability, discharge LOS would be reduced (Figure 3). We discuss the findings for these two scenarios in the following section.

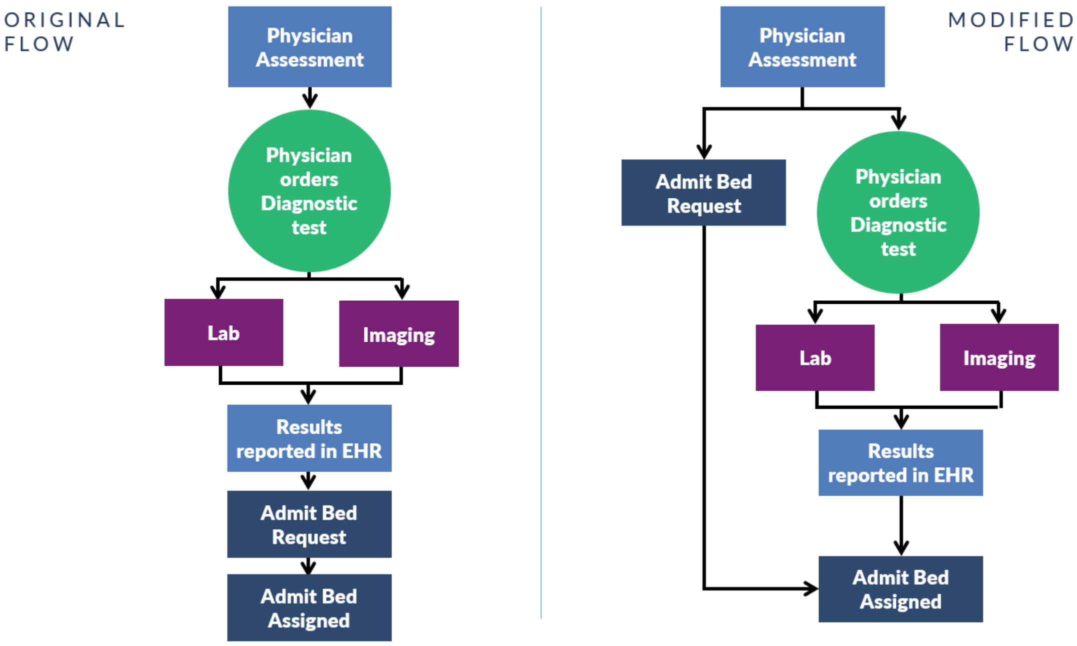

Figure 3 This diagram compares the original ED flow with the modified Rapid-Admit protocol (Image Copyright: Author).

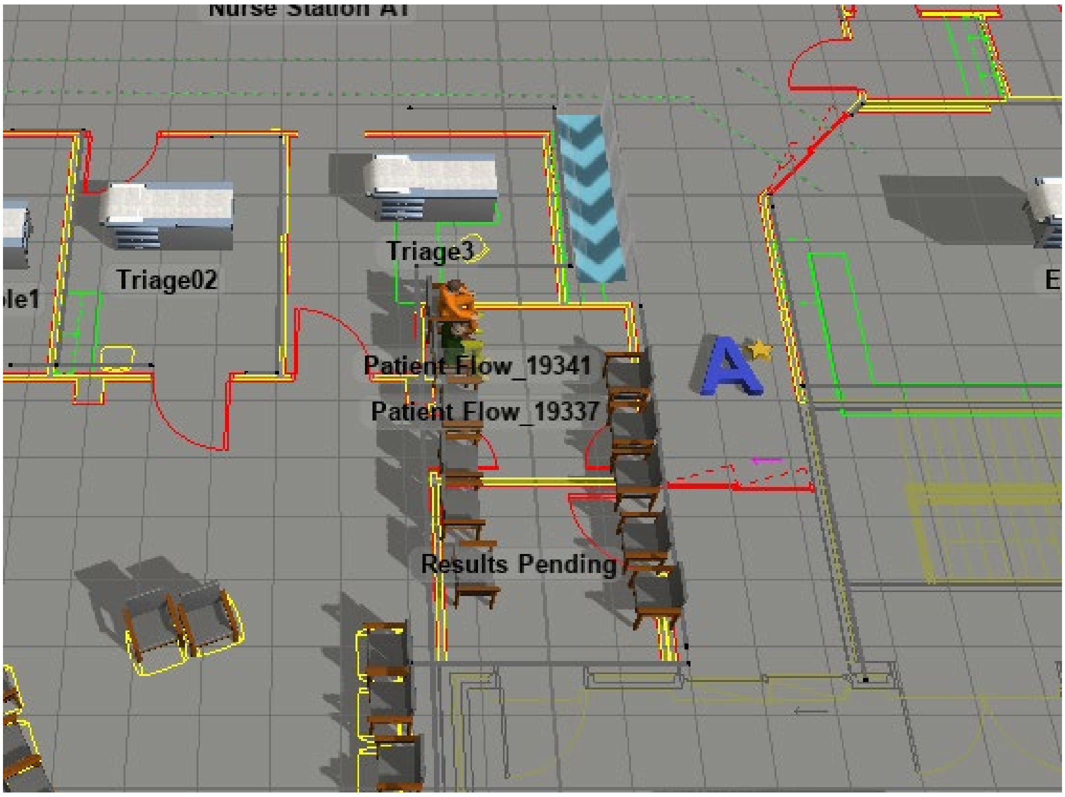

Figure 4 The Results pending area was created in the ED to evaluate its outcome on patient LOS (Image Copyright: Author).

Secondly, we examined the impact of a results-pending area as a space for less acute patients to wait for imaging or lab results instead of occupying the exam room. This space was assumed to replace an existing low-utilized office area within the ED and provided 11 seats for the patients (Figures 4-5). The hypothesis was that this would lead to a reduced LOS for admit patients due to more exam room availability and no impact on discharge LOS.

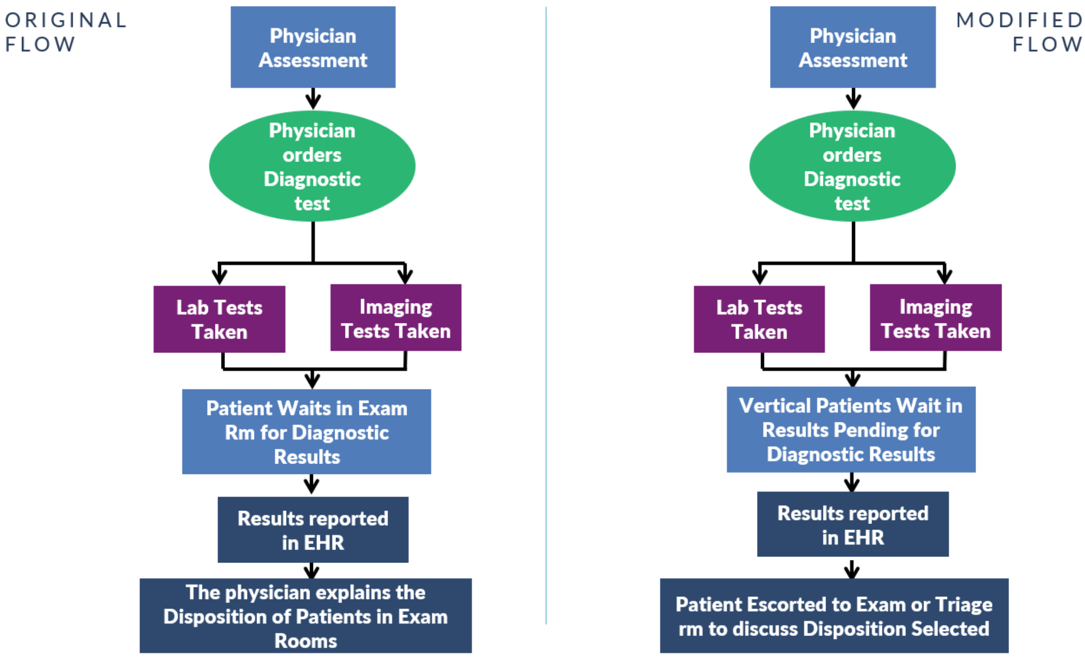

Figure 5 This figure compares the original and modified patient flow by implementing the results-pending improvement (Image Copyright: Author).

3. Results

The base model and the fast-admit scenarios were compared with the base model regarding patient LOS, Arrival-to-bed requests (order for admission), and Arrival-to-inpatient bed assigned milestones. Findings showed that the median LOS decreased by 16% and 6% for admitted and discharged patients, respectively (Figure 6). Further, Arrival-to-Bed request and Arrival-to-Bed-Assigned average minutes improved by 57% and 37%, respectively (Figure 7).

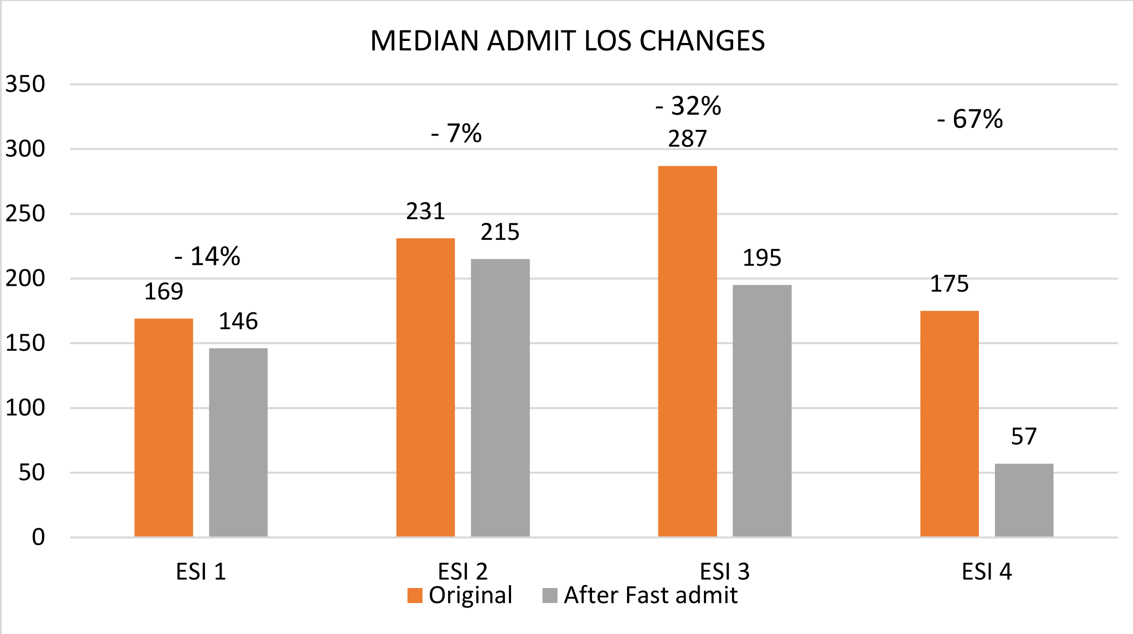

Figure 6 Median admit LOS comparison between the base model and after the Rapid-Admit modification (Image Copyright: Author).

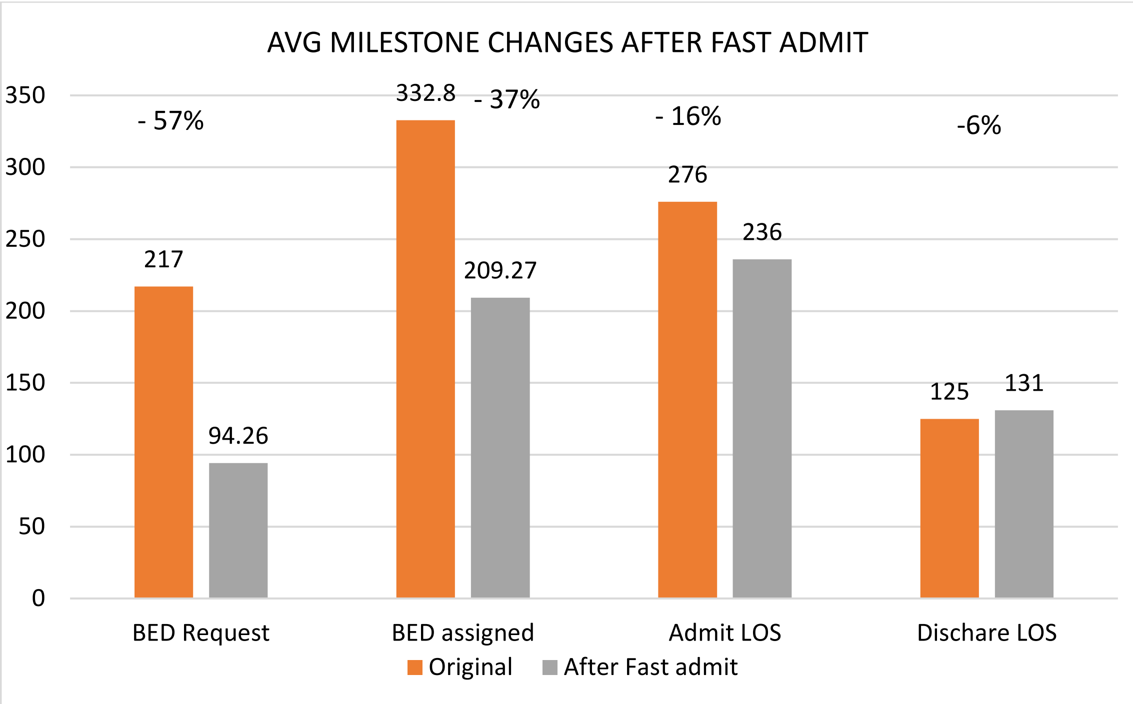

Figure 7 Average milestone changes after the rapid-admit adjustments (Image Copyright: Author).

Next, the model explored the impact of a results-pending strategy for low-acuity discharge patients. Figure 8 shows the average length of stay (LOS) times for admit patients, suggesting an average 32% reduction across all ESI levels (ESI 1 = - 20%, ESI 2 = - 20%, ESI 3 = - 37%, and ESI 4 = - 50% LOS variations from current to proposed state). Figure 9 shows the impact of this implication on discharge patients across different ESI levels (ESI 2 = 0%, ESI 3 = 1%, ESI 4 = 4%, and ESI 5 = 0% variations from the current to the proposed state). The results pending implications did not substantially improve the discharge LOS (AVG increase by 1%). Additionally, this modification improved the exam room availability by 22% compared to the base model.

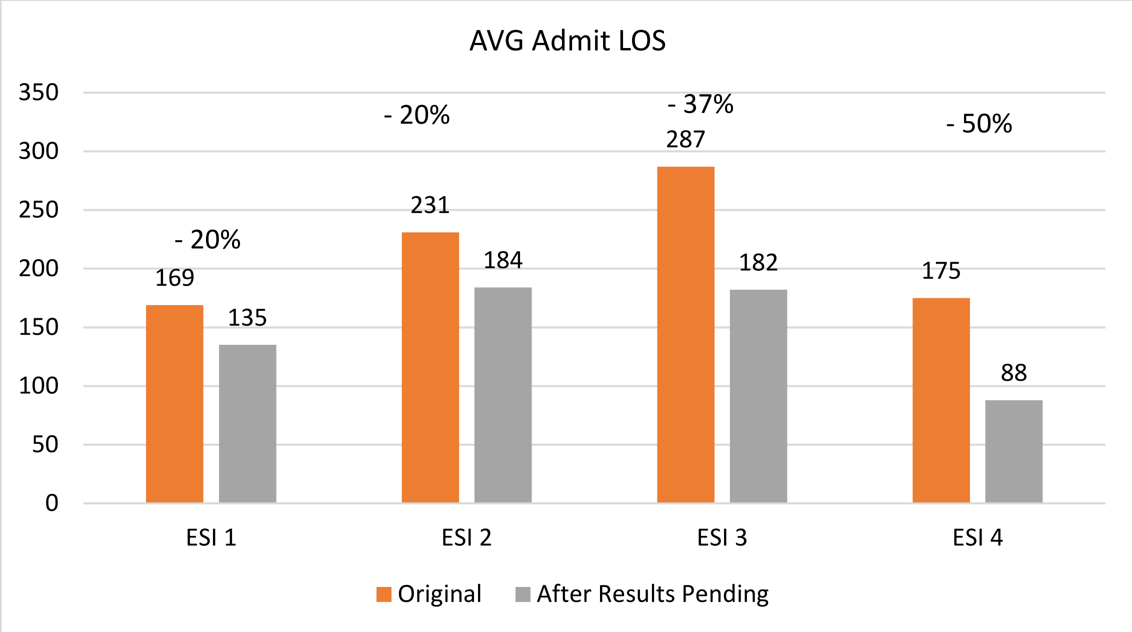

Figure8 Comparisons of average admit patient LOS across the base model and after the results-pending implementation (Image Copyright: Author).

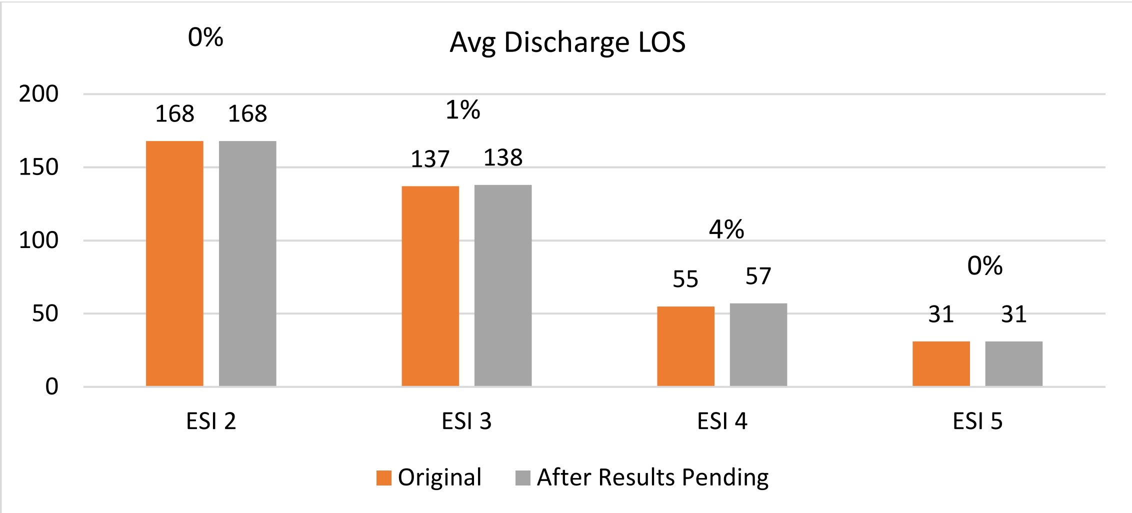

Figure 9 This diagram compares the average LOS for discharge patients before and after the results-pending implementation (Image Copyright: Author).

4. Discussion

A growing body of evidence suggests the association between ED crowding and unfavorable quality of care outcomes. These adverse outcomes include patients left without being seen, readmission, patient mortality, increased chances of admission or transfer, or reduced satisfaction (Amarasingham et al., 2010; Boulain et al., 2020; Quinn et al., 2007; Singer et al., 2011; Zilm et al., 2010). Therefore, suitable demand-capacity matching and adapted admission protocols are strategies for reducing ED patients' Length of Stay (LOS) and improving boarding times.

Improved boarding times associates with reduced ED crowding (Amarasingham et al., 2010; Patel et al., 2014). In their study, Patel et al. (2014) showed that a leadership-based program for expediting the inpatient admission process for ED patients significantly decreased ED LOS and patient satisfaction.

Several scenarios may produce delayed boarding times, including inadequate inpatient beds, inadequate staffing, or prolonged room turnover. The introduction of rapid-admission protocol (RAP) recreates an essential milestone in ED flow and safety improvement. In this protocol, instead of fully completing all diagnostic tests before departure, the patient will be admitted to the hospital unit as soon as a bed is available, even before complete evaluations (Amarasingham et al., 2010). In their study, Amarasingham et al. (2010) explain how their team of clinical and administrative leaders developed a RAP to ease the transfer of admitted patients to the internal medicine service. After the protocol modifications, the overall ED boarding times decreased from 360 minutes to 270 minutes. Further, the time to admission orders was reduced from 210 minutes to 75 minutes after the intervention. Similarly, Quinn et al. (2007) found that the RAP implementation reduced the ED LOS by 10.1 minutes, resulting in an average of 4.3 hours of extra bed availability.

In agreement with previous reports (Amarasingham et al., 2010; Quinn et al., 2007; Spaite et al., 2002), the simulation results found reduced LOS for admitted patients when administering the RAP. However, healthcare facilities may struggle to implement RAP (Spaite et al., 2002). Successful implementation involves focusing on and developing change management planning, limiting clinical roles, requiring direct communication, and developing clear boundaries for patient responsibility (Amarasingham et al., 2010; Spaite et al., 2002). Future studies are recommended to explore potential barriers to executing RAP in EDs.

The limited health and design literature highlight physical space's importance in process ED outcomes. Aligned with the existing literature (Bryant, 2013; White et al., 2014; Zilm et al., 2010), the simulation results illustrated how the application of a results-pending room as an internal waiting area for low acuity patients reduced admit LOS and improved exam room availability for high acuity patients. For instance, Zilm et al. (2010) diverted low-acuity patients to a flexible "results-waiting" care area as one of their process intervention strategies. Combined with other strategies, this intervention reduced the number of Left without being seen (LWBS) and LOS. Bryant (2013) employed a retrospective descriptive comparative design showing that the average LOS for patients in the results-pending treatment areas was 31 minutes faster than those treated in intermediate care. This design implication can be integrated into future ED process improvement and system engineering interventions to reduce ED overcrowding.

DES is essential in healthcare settings to detect and evaluate healthcare systems' unpredictable and variable nature. The findings from this study displayed that the application of DES provides a cost-effective instrument to assess and inform future design decisions using current process data. Similar to previous studies (Cai & Jia, 2019; Han et al., 2010; Oh et al., 2016; Shim & Kumar, 2010b; Swan et al., 2019; Valipoor et al., 2021b), DES was notably worthwhile in evaluating the impact of multiple processes, design solutions, and proposing optimal scenarios for the ED.

Consistent with prior studies (Brailsford & Hilton, 2001), simulation modeling improved communication between researchers and healthcare professionals. Remarkably, the 3D environment of the FlexSIM software, combined with its video exportation capabilities, enhanced communication with the researcher, architects, and team members.

5. Limitations

Studies show that simulation applications in healthcare will continue to grow and strengthen. Despite the promising outlook of DES in healthcare studies (Cai & Jia, 2019; Mielczarek & Uziałko-Mydlikowska, 2012; Swan et al., 2019), its application still faces challenges. The implementation corresponds to how healthcare facility managers or decision-makers perceive the method's credibility and dependability. This information aligns with other researchers (Fone et al., 2003), highlighting only a few successful implementations of simulation modeling by health practitioners and policymakers. To improve this limitation, researchers need to educate and encourage owners on the return on investments achieved by such studies in the preliminary phases of design development. Attributable to the limited sample size, the findings from this study would not allow for generalizability. While the outcomes measured may have suggested an association, they do not confirm causality. Future studies may benefit from a larger sample size or a more robust analysis considering different layouts and patient distributions.

6. Conclusion

If possible, discharge guidelines for Eds must reflect various ideas from evidence-based design research. Definitive evidence for health facility design remains relatively scarce, and there are still discussions on the evidence needed per project type or health system. While several investigations have explored the impact of patient flow strategies on ED process outcomes through DES, the examination of design alternatives and RAP on ED crowding needs to be more extensive. Thus, this study aimed to introduce and explore DES as a data-driven tool that may influence design decisions, improve internal and external communication, and suggest policy implementations.

RAP and Results-Pending strategies reduced boarding times and LOS for patients to be admitted, which are expected to enhance ED crowding, patient safety, and patient satisfaction. Further studies are suggested to explore patient and staff opinions of similar interventions. Design guidelines could emphasize recognizing results-pending spaces as a critical element for enhancing delivery and quality of care. Further investigation into the suitable size and attributes of a patient results-pending room is also necessary. While this study was conducted at one ED, the flow diagrams illustrated similar patient flows in other EDs. However, to generalize these findings, future studies should be repeated with an adequate representative sample of EDS across different regions, patient types, and demographics.

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Resume

Zahra Zamani is a senior design researcher and healthcare planner in BSA LifeStructures. Zahra is passionate about evaluating the impact of design and planning decisions on human experience, operational efficiency, satisfaction, health, and well-being. Zahra's research provides designers and planners with the best possible design solution to the problems after studying and analyzing the project content. She also enjoys exploring the human dimensions and anthropology, social needs, and comfort levels in connection to design. She has published and presented her research findings in multiple journal papers and international conferences, including Environmental Design Research Association (EDRA), NEOCON, Healthcare Systems Process Improvement (HSPI), and Healthcare Design Conference.