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An Agent-based Simulation for Workflow in Emergency Department

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Abstract — **Patients always come to an Emergency Department (ED) to seek immediate medical care. Conversely, usually they experience prolonged waiting for nurses, physicians or radiology/lab procedures. There is a lot of public and private pressure on ED to improve the quality and efficiency of health care. As a result, ED workflow is under continuous changes. However, ED administrators usually lack a convenient decision support tool to evaluate the impacts of a changed workflow. They often find unexpected ED performance degeneracy after some workflow changes. This paper introduces an agent-based simulation which models various phases in the ED workflow, such as triage, nurse screen, resident exam, attending exam, lab/radiology, and disposition. The purpose of this paper is two-fold: (1) to develop an agent-based simulation to allow free exploration of the ED performance under various settings; (2) to characterize and study the ED performance under different settings of the triage process and radiology procedure process. The analysis of two simulated cases is presented to illustrate how the changes of the triage process and the radiology process impact the patient throughput time and the other critical performance measures. The simulation outcome and empirical data demonstrate a similar change pattern after a modification in the triage process. The findings in this study indicate that the agent-based simulation can be used by ED administrators to plan changes, locate bottlenecks, and study the non-linear relationships among different phases in the ED workflow.**

I. Introduction

An emergent department (ED) (a.k.a, emergency room, emergency ward, or accident & emergency department) is a clinical unit to treat patients with urgent needs of medical care[1]. Due to the pressure to provide effective and comprehensive patient care in a time-abbreviated manner, the ED workflow is usually embedded with a lot complexity [2]. The actual practice in ED is anything but linear due to factors, such as [1][3][4][5]:

- The variation in the number and conditions of new patients
- Simultaneous demands and competing priorities for caregivers
- Deficiency in resources (e.g., bed space, equipment or personnel)
- Inefficient communication among caregivers
- Multiple delays (e.g., waiting for consultants to arrive, tests to be run, medicine to take effect, family to arrive, inpatient bed to be ready)
- Interruptions and shift changes

Computer models are used extensively in the health care domain [6]. Popular approaches include decision analysis, Markov process, mathematical modeling, systems dynamics and discrete event simulation [6][7]. The drawback of the common modeling approaches is that they tend to overlook the effect of the naturalistic human decision making and behaviors on the performance of healthcare process. In addition, stochastic features in the individual steps in health care process are usually not fully incorporated. The agent-based simulation offers a complementary perspective to model the process of health care domain [7][8][9]. The purpose of this paper is two-fold: (1) to develop an agent-based model to simulate the ED workflow and allow free exploration of the workflow performance under different settings; (2) to characterize and study the change in the healthcare performance under different settings of the triage process and radiology procedure process.

II. Methods of Simulation

This agent-based simulation was modeled using an open source software package Netlogo 4.0.3. Fig 1 shows a screenshot of the simulation and the simulated ED workflow. The whole patch field is divided by a series of grey and green columns which represent different phases in ED patient care. When patients are waiting for service from one type of healthcare providers, they will stay in the corresponding grey column. When the caregiver they need is available for them, they will move forward in the corresponding green column.

A. Simulated Workflow

First patients arrive at the ED front door and wait in line to be triaged. The triage nurse(s) will triage patients on a first-come-first-serve basis. After triage, a patient will stay in the waiting room until a nurse takes him/her to a bed. In the patient's bedside, the nurse will screen his/her medical condition. After that, a patient will wait until a physician is available to give him/her an examination and reach a medical decision. When the condition of a patient is simple, he/she will

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then be discharged by his/her nurse directly. When the condition of a patient is complicated, a physician may place a radiology order. In this case, a patient will need to complete the radiology procedure and a physician needs to review the results before they get discharged by nurses.

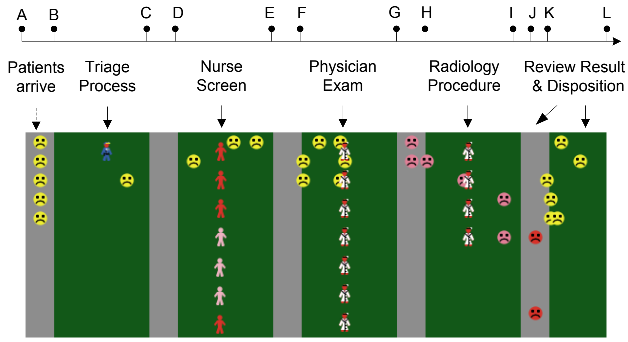

Fig 1. Simulated ED workflow and simulation screenshot.

B. *Agents and Rules*

Patients and each type of healthcare providers were modeled as different types of agents which have different appearance and rules:

1) Patients: Patients are represented using the yellow sad face in the simulation. They are passive since their progress in the ED is largely depended on the availability and efficiency of the healthcare providers. A patient's icon will turn pink if their physician ordered radiology for them. A patient's icon will turn red after radiology procedure to indicate that they are waiting for their physicians to read the results. After the physicians review the results, the icon will come back to yellow.

2) Triage Nurses: The icons in the first green column in Fig 1 indicate triage nurses. When they are busy, the icon faces will turn red. Triage nurses triage patients on the first-come-first-serve basis according to their arrival time.

3) Bedside Nurses: The icons in the second green column in Fig 1 indicate bedside nurses. When they are busy, the icons will turn red. When bedside nurses are not busy, they will first check whether any of their patients are ready to be disposed from ED. If so, they will conduct the disposition procedure. For the ready-to-dispose patients, their nurses will serve them on a first-come-first-serve basis according to the time that they become ready to be disposed. If none of a nurse's current patients need to be disposed, the nurse will designate him/herself to a new patient and give the patient a medical screen. For the new patients, nurses serve them on a first-come-first-serve basis according to their triage completion time. Only a patient's designated nurse is responsible to conduct discharge procedure for him/her.

4) Physicians: The icons in the third green column in Fig 1 indicate physicians. When they are busy, the icons will turn red. When physicians are not busy, they will first check to see if any radiology results of their current patients need to be reviewed. If so, they will review the results on a first-come-first-serve basis according to the radiology completion time. If there is no radiology result waiting be reviewed, a free physician will designate him/herself to a patient who has finished the nurse screen and give the patient an examination. They do this on a first-come-first-serve basis according to the patients' nurse-screen-completion time. Only a patient's designated physician is responsible to review his/her radiology result.

5) Radiologists: The icons in the fourth green column in Fig 1 indicate radiologists. When they are busy, the icons will turn red. When radiologists are not busy, they will conduct radiology procedure on patients on a first-come-first-serve basis according to the physician orders.

C. *Simulation Inputs*

Users of this simulation can adjust four aspects of the workflow characteristics. The default values of these simulation inputs are in parentheses following each input name. The default values were chosen based on the observation in the ED at the University of Virginia (UVa) Health System.

1) Patient Arrival Characteristics

- Initial patient number (2): This indicates the initial number of patients at the ED front door.
- Number of peak hours per day (8): This indicates the number of daily busy hours in an ED. One day is divided into a consecutive busy period and a consecutive relative idle period.
- Number of patients per hour during peak hours (15): This indicates the hourly patient arrival rate during peak hours. Whether there is a patient arriving at the ED door at each minute is randomized with the constraints that statistically the hourly patient rate during the peak hours is equal to this number.
- Number of patients per hour during non-peak hours (5): This indicates the hourly patient arrival rate during the relative idle period.
- Patients' maximum waiting time (120): If patients wait too long before they see a triage nurse, they become inpatient and leave ED. This parameter indicates the maximum minutes that a patient will wait to see a triage nurse.

2) Triage Characteristics

- Number of triage nurses (1): This indicates the number of triage nurse in the initial state.
- Average triage time (6): This indicates how long in average it takes a nurse to triage a patient.
- Random variation of triage time (5): This indicates the extent to which the triage duration can vary.
- Whether allow adjustment of triage nurse number (Yes): This indicates whether the ED will assign an extra nurse to do triage when there are too many patients waiting in door and take away extra triage nurses when there are few patients waiting for triage.
- Upper limit for triage adjustment (10): The length of waiting line in door which will trigger one more triage

nurse to appear.

- Lower limit for triage adjustment (2): The length of waiting line in door which will trigger a triage nurse to leave. Note that at least one triage nurse will always be at door to do triage.
- Maximum number of triage nurses (2): The maximum triage nurse that can work at the same time.

3) Nurse Care Characteristics

- Number of beds (60): Total number of beds in an ED.
- Number of bedside nurses (12): Number of nurses in an ED.
- Average nurse screen time (20): The time it takes a nurse to bring a patient to bed and give him/her a medical screen.
- Random variation of nurse screen time (6): This indicates the extent to which the duration of nurse screen can vary.
- Average disposition time (15): the time it takes a nurse to conduct the disposition procedure for a patient.

4) Physician Care Characteristics

- Number of Physicians (8): Number of physicians in an ED.
- Average physician exam time (20): The time it takes a physician to perform a medical examination on a patient.
- Average radiology review time (18): The time it takes a physician to review the result from a radiology order.

5) Radiology Order Characteristics

- Radiology likelihood (50): This indicates the likelihood that a physician will place a radiology order for a patient.
- Number of radiologists (4): How many radiologists can perform the radiology procedure in parallel.
- Average radiology procedure time (30): the minutes it takes a radiologist to perform the radiology procedure.

D. Simulation Outputs

The simulation outputs are the performance measures of the ED workflow. Fig 2 and Fig 3 are examples of the output plots. The meaning of the legends for Fig 2 is intuitive. The meaning of the legends in Fig 3 is listed as follows (the time points are referred to what defined in Fig 1):

- Entire stay in ED (A -> L): This indicates total throughput time for a patient – from the patient arrival to his/her departure.
- Time to be in bed (A -> D): The time from a patient's arrival to the time he/she has a designated nurse.
- Time to see resident (A -> F): The time from a patient's arrival to the time he/she has a designated physician.
- Waiting time in door (A -> B): The time from a patient's arrival to the time he/she is called by a triage nurse.
- Time in waiting room (C -> D): The time from a patient finishes triage to the time he/she has a designated nurse.
- Radiology waiting time (G -> H): The time from a radiology order is placed for a patient to the procedure actually starts.
- Discharge waiting time (K -> L): The time from a patient becomes ready to be disposed to the time his/her is available to conduct the disposition procedure.
- Resident waiting time (E -> F): The time from a patient finishes nurse screen to the time a physician assigns him/herself to the patient.

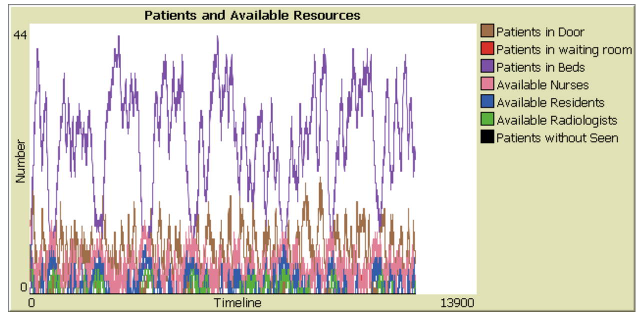

Fig 2. Patients and available resource on each minute

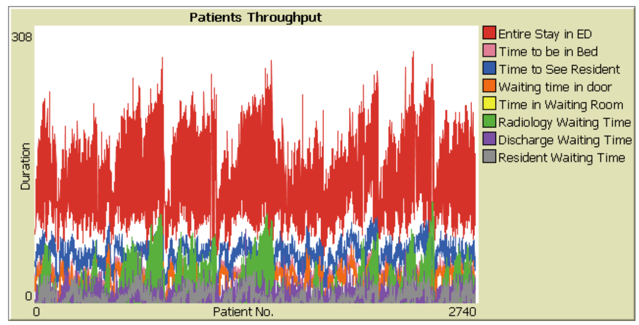

Fig 3. Patient throughput time for each disposed patients.

E. A Case Study

To illustrate how this simulation can be used to understand the healthcare performance changes and plan changes in advance, we tested the impact of two critical work processes in ED: the triage process and the radiology process. For triage process, we compared the performance measures with and without the adjustment of the triage nurses. Without adjustment, there was only one triage nurse working at all times. With triage adjustment, one additional triage nurse would appear to work parallel with the other one when the waiting line exceeded 10 patients and leave when the waiting patients were fewer than 2. For the radiology process, we manipulated the radiology procedure time. In the controlled condition, the radiology procedure time was 30 minutes; in the two experimental conditions, it was reduced to 28 minutes and 26 minutes, respectively. The purpose of this analysis is to examine the impact of a small reduction of radiology procedure time. All the simulation inputs were kept at the default values except for the testing factors.

To let the simulation reach a stable state, the results from the first day (1440 minutes) and from the first 200 disposed patients were excluded from the analysis. The data used for analysis were the 2nd to 5th day (i.e., 1441 - 7200 minute) in the "patient and available resources" plot and the 201st to 1199th disposed patients in the "patient throughput" plot.

III. Results

A. Triage Adjustment

Table 1 shows the resulting healthcare quality measures with and without the adjustment of triage nurse number. Only the most relevant measures were reported here. The 2-tailed independent sample t-tests were used to analyze the statistical significance of the change. Patients waiting in door for triage, and patients left without being seen were significantly more without triage adjustment. Consistently, the patient waiting time in door and the entire stay time were both much longer without triage adjustment. Interestingly, the benefit of triage adjustment was larger to the waiting time in door than the entire stay time. This result indicated that the other processes in the workflow might not catch up with the improved triage performance. Patients in waiting room and patients in bed were both significantly more in the condition with triage adjustment. The waiting time for nurses, physicians and radiologists were all longer when with triage adjustment. This result implied that the workload of nurses, physicians and radiologists were higher when with triage adjustment and they could not see new patients as soon as the condition without triage adjustment. Further, the difference of radiology waiting time was the largest among the three waiting time, which indicated the radiology process was the most significant bottleneck in triage adjustment condition.

TABLE 1
Patients Numbers and Throughput Time with and without Triage Adjustment

Measures	Triage Adjust	Mean	STD	t-test
Patients in Door	Not adjust	23.98	10.63	t=133.98
	Adjust	6.14	3.82	p<.0001
Patients in Waiting Room	Not adjust	0.00	0.00	t=-12.09
	Adjust	0.03	0.22	p<.0001
Patients in Bed	Not adjust	12.43	2.09	t=-114.80
	Adjust	24.54	8.70	p<.0001
Patients Left Without Seen	Not adjust	0.07	0.25	t=22.90
	Adjust	0.00	0.00	p<.0001
Entire Stay in ED	Not adjust	186.73	41.47	t =24.05
	Adjust	137.70	49.37	p<.0001
Waiting Time in Door	Not adjust	98.75	31.18	t =24.05
	Adjust	20.20	12.36	p<.0001
Time in Waiting Room	Not adjust	0.00	0.00	t= -6.54
	Adjust	0.13	0.65	p<.0001
Resident Waiting Time	Not adjust	0.01	0.12	t = -27.40
	Adjust	6.70	7.72	p<.0001
Radiology Waiting Time	Not adjust	0.28	1.50	t=21.48
	Adjust	16.73	24.16	p<.0001

B. Radiology Efficiency Adjustment

Table 2 shows the resulting healthcare quality measures under the conditions with different radiology procedure time – 26 min, 28 min, and 30 min. The one-way ANOVA was used to test the statistical significance of the change in radiology procedure time. Individual contrasts were analyzed using Dunnett's test between each experimental condition and the controlled condition. The number of available radiologist, the radiology waiting time, and the entire stay time in ED improved significantly in both 28-min and 26-min condition compared to the controlled condition. In addition, it seems that the larger the reduction in radiology time, the larger the improvement in these measures. A 2 – 4 min change of radiology procedure time brought a large change in the total throughput time (10.38 – 17.71 min).

The change in the measures of physician care was interesting. The waiting time for physician examination was significant less in the 28-min condition than the 30-min condition. However, after further reduction of radiology procedure time, this difference (i.e., between 26-min and 30-min condition) became insignificant. This result highlighted the importance of coordinating care between the radiologists and physicians. When their paces were matched well, such as, in the 28-min condition, the performance of one party can benefit from the performance improvement of the other party.

The change in radiology efficiency, did not affect the nursing performance significantly, there was no significant change in number of patients in waiting room and patients' waiting time in waiting room.

TABLE 2
Patients Numbers and Throughput Time under Different Radiology Efficiency

Measures	Radiology Procedure Time		Mean Difference (Others - 30min)	Sig. (p)
Patients in Door	26 min	30 min	0.15	0.05
	28 min	30 min	0.06	0.52
Patients in Waiting Room	26 min	30 min	0.00	0.86
	28 min	30 min	0.00	0.59
Patients in Beds	26 min	30 min	-3.54	<.0001
	28 min	30 min	-4.79	<.0001
Available Radiologists	26 min	30 min	0.63	<.0001
	28 min	30 min	0.56	<.0001
Entire Stay in ED	26 min	30 min	-17.71	<.0001
	28 min	30 min	-10.38	<.0001
Waiting Time in Door	26 min	30 min	0.12	0.96
	28 min	30 min	3.75	<.0001
Time in Waiting Room	26 min	30 min	0.06	0.12
	28 min	30 min	-0.01	0.93
Resident Waiting Time	26 min	30 min	-0.68	0.06
	28 min	30 min	-1.91	<.0001
Radiology Waiting Time	26 min	30 min	-14.57	<.0001
	28 min	30 min	-10.86	<.0001

IV. Discussion

This paper reports the simulated ED performance changes under different conditions of the triage process and the radiology process. The results suggest that triage adjustment policy can improve overall healthcare efficiency and increase ED revenue. The patient total throughput time reduced from 186.73 minutes to 137.70 minutes. In addition, there was no patient left with being seen in the triage adjustment condition, while every 100 minutes 7 patients in the condition without triage adjustment will leave ED before triage. The simulated result is consistent with the empirical finding in the UVa ED. Recently, the UVa ED implemented the triage adjustment policy with the goal of reducing the left-without-seen patients. To their surprise, they not only found the left-without-seen patients reduced, the throughput time also decreased.

Not only can this simulation be used to plan and trigger beneficial changes, it can also help user to understand the impact of the changes and identify further optimization strategies. In this case, the simulation result indicates that the reduction of the total throughput time was still less than the reduction in the waiting time for triage. This result was mainly caused by the increased radiology waiting time. If the ED administrators want to further reduce the total throughput time, the radiology process will need to be improved.

When manipulating the radiology procedure time, we found that a small change in the radiology efficiency can bring a larger change in the total throughput time. In addition, we found that the change from 30 to 26 minutes seems to be larger than the change from 28 to 26 minutes. This indicates that the overall healthcare performance is constrained by multiple factors. If other processes cannot catch up with the improvement in one process, the benefits of that improvement will be harmed. In this case, the interaction between the radiology process and the resident process was interesting and worth further studying.

V. Conclusion

As an agent-based simulation, the behaviors of all the agents in this simulation, such as, patients, nurses, physicians, and radiologists, are specified by simple rules instead of the complex mathematical formula in traditional discrete events simulation. Although ED administrators in general do not have strong mathematical background, they will still be able to understand how this simulation works and will be willing to trust its results [10]. This agent-based simulation offers a convenient tool for administrators in ED to study the workflow and test the impact of potential changes. The input parameters of this simulation can be easily tailored to a specific ED condition. It is particularly useful for understanding the interaction among different individual processes and the non-linear relationship between the change in one individual process and the change in the overall performance.

To meet the needs of patients from a diverse population and medical condition, the actual ED workflow is much more complicated than what was modeled here. This simulation can be enhanced by making the workflow more complete and realistic and by adding more rules (i.e., characteristics of clinical decision making) for each type agent. For instance, healthcare providers do not always serve patients in a first-come-first-serve basis. In contrast, they need to consider the acuity of patients. Another interesting aspect should be modeled is that the radiology department in a hospital usually has a limited working hour. If an order is placed after the working hour, then a patient usually needs to wait until the next day. All in all, to increase the validity of this simulation, future work needs to be done to make it more customizable and with higher fidelity.

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References

[1] M. Smith, C. Feied, "The emergency department as a complex system," 1999, http://www.necsi.edu/projects/yaneer/emergencydeptcx.pdf
[2] S.C. Brailsford, V.A. Lattimer, P. Tarnaras, J. C. Turnbull, "Emergency and on-demand health care: Modeling a large complex system," *Journal Operation Research Society*, vol. 55(1), pp. 34-42, Jan 2004.
[3] Joint Commission Perspectives on Patient Safety, "Sharing information at transfers: Proven technique to aid handoff communications," 2005, 5(12): 9-10. http://www.ccforpatientsafety.org/31156/
[4] J.G. Anderson, "Social, ethical and legal barriers to E-health," *International Journal of Medical Informatics,* vol. 76(5-6), pp. 480-3. May-June 2007.
[5] R.W., Schafermeyer, B.R. Asplin, "Hospital and emergency department crowding in the United States," *Emergency Medicine,* vol. 15(1), pp. 22-7, February 2003.
[6] D. Fone, S. Hollinghurst, M. Temple, A. Round, N. Lester, A. Weightman, K. Roberts, E. Coyle, G. Bevan, S. Palmer, "Systematic review of the use and value of computer simulation modeling in population health and health care delivery," *Journal of Public Health*, vol. 25(4), pp. 325-35. December, 2003.
[7] A. K., Kanagarajah, P. A. Lindsay, A. M. Miller, D. W. Parker, "An exploration into the uses of agent-based modeling to improve quality of healthcare," *International conference on complex systems*, 2006.
[8] A. K., Hutzschenreuter, P. A. N. Bosman, I. Blonk-Altena, J. V. Aarle, H. L. La Poutré, "Agent-based patient admission scheduling in hospitals," *Proceedings of the 7th international joint conference on autonomous agents and multiagent systems*, 2008.
[9] M. R. Poynton, V. M. Shah, R. BeLue, B. Mazzotta, H. Beil, S. Habibullah, "Computer terminal placement and workflow in an emergency department: An agent-based model," *Proceedings of the complex systems summer school*, 2007.
[10] J. D. Lee , K. A. See, "Trust in automation: Designing for appropriate reliance," *Hum Factors,* vol. 46(1), pp. 50-80. Spring, 2004.