Estimating the Right Allocation of Doctors in Emergency Department

Mohd Ridzwan Zulkifli[1], Muthukkaruppan Annamalai[1], Kassim Isahak[1] and Rashidi Ahmad[2]

[1]*Universiti Teknologi MARA (Shah Alam), Malaysia, ridz.binary@gmail.com, {mk; isahak}@tmsk.uitm.my,*

[2]*University Malaya Medical Centre, Kuala Lumpur, Malaysia, rashidi@ummc.edu.my*

ABSTRACT

Emergency Department (ED) provides acute care to various medical and surgical conditions. In a typical ED, there are three management zones: Red, Yellow and Green zones for attending patients with critical, semi critical and non-critical illness and injuries, respectively. The problem is staffing each zone with adequate doctors (the scarce resource) to ensure the ED is able to function as a reliable organisation. Consequently, this paper presents a useful way to estimate the right allocation of doctors in ED through Discrete-Event Simulation (DES) implemented using Arena. The estimation is based on patients' waiting time and doctors' utilisation rate. The basis of the simulation is drawn from Queuing Theory and Theory of Constraints. The case study is the University Malaya Medical Centre (UMMC). Seven scenarios based on real-life situations are simulated and analysed. The results show that the right allocation to the Red, Yellow, and Green Zones in UMMC-ED are two, four and two doctors, respectively. The findings will serve as the basis to plan for future work on repositioning relatively free doctors from one zone to another zone that is facing temporary overcrowding emergencies.

Keywords: Emergency Department, Discrete-Event Simulation, Queuing Theory, Theory of Constraint.

I BACKGROUND

Emergency Department (ED) is a facility in hospital that operates around the clock to provide initial treatment with illnesses and injuries that could be life threatening and require immediate attention. In a typical ED such as in our case study, the University Malaya Medical Centre (UMMC), the arriving adult patients are triaged according to their severity, and assigned to one of the three zones. Patients with critical condition will be directed to the Red zone, semi critical conditions to the Yellow zone, and non-critical conditions to the Green zone. They urgency of care is reflected in the maximum waiting time that is allowed for patients to receive attention and treatment as shown in Table 1.

ED is staffed with few doctors who are supported by many paramedics and nurses. The healthcare management in ED is highly dependent on the doctors because only they are authorised to make healthcare decision for patients. Therefore, a key challenge in the management of ED is to estimate the right number of doctors to allocate in each zone especially during the peak hours. On one hand, fewer doctors in ED will cause insufficient capacity to supply demand, which leads to doctors' fatigue and starve patients needing emergency care. On the other hand, many doctors in ED will cause excessive capacity to supply demand, which leads to the under-utilisation of the scarce resource. Hence, staffing each zone with the right number of doctors is necessary to ensure the doctors are maximally utilised and patients are treated within the allowed waiting time. According to Martin, a good utilisation rate of resources in the service sector is between 70 and 80 percentages (Martin, 2010).

Table 9. Maximum Patient Waiting Time for Each Zone

Zone	Description	Max. Waiting Time
Red	Critical – Immediate threat to life	0 minute
Yellow	Semi Critical – Prompt care needed	30 minutes
Green	Non-Critical – Can wait	90 minutes

Each ED management zone has random arrival of patients, multiple channels of arrival, random cases of patient severity and multiple stages of management. While some facilities for investigation are available within a zone, some are shared in common. These factors increase the complexity to estimate the right allocation of doctors to each zone.

In dealing with the above complexity, we resort to Queuing Theory (QT) and Theory of Constraints (ToC) to construct a Discrete-Event Simulation (DES) model. The computer model is executed and studied for various scenarios in order to estimate the doctors required in ED.

II CASE STUDY

Doctors are the key resources in ED. The doctors in UMMC-ED comprise specialists, physicians and medical officers, who are allocated to the Red, Yellow and Green zones, respectively. Specialist is a doctor who is specialised in emergency medicine and has vast experience in emergency care. Physician has medical and surgical skills, and is on the way to become a specialist. Medical officer is a person who has a medical degree qualification and registered to Malaysia Medical Council. There are fewer specialists in ED compared to physician and medical officers. In teaching hospitals like UMMC, the medical officers consist of trainee doctors who are supervised by specialists and/ or physicians.

The doctors work in shifts. For example, in UMMC-ED, the morning, evening and overnight shifts are 0800 to 1500 (7 hours), 1500 to 2200 (7 hours) and 2200 to 0800 (10 hours), respectively. It has been observed that the morning and evening shifts are more crowded compared to the overnight shift; a reason for the longer overnight shift period.

In addition, the following constraints have been stipulated for estimating the allocation of doctors in UMMC-ED. Each zone is allocated a minimum number of two doctors per shift. The number of doctors can be increased to a maximum of nine by involving additional physicians and medical officers, more of the latter.

III RELATED WORK

We can regard the estimation of the doctors required in ED during peak hours as a form of capacity planning of vital resource (i.e., doctors) to support the ED management.

Computer simulation is a popular tool used by decision makers to analyse the constructive management of resources in complex systems, but the simulation model about a process that is supported by theory and practice must be first constructed (Maria, 1997). In this work, the basis of the ED simulation model is drawn from two theories: Queuing Theory (QT) and Theory of Constraints (ToC).

QT has been applied in scheduling and staffing in healthcare applications (Fomundam & Herrmann, 2007). The theory relates the queue discipline and network measuring variables such as arrival time, waiting time, queue length, service time, service channel, to define the services and their relationships. Such measures are fundamental to the understanding of patient flow and to estimate staff allocation in ED. For example, Exadaktylos, Evangelopoulos, Wullschleger, Bürki, & Zimmermann (2008) have studied the minimum number of staff required is based on the average patient arrival and average service time. In Green, Soares, Giglio, & Green (2006), the estimation of staff is based on average service time and the average number of patients who left without being seen. In McManus, Long, Cooper, & Litvak (2004), the bed utilisation is used as an additional measure.

Besides scheduling and staffing, there are also works that applied QT to reduce queue waiting time or sometimes referred to as the length of stay (LoS) (Lewis & Edwards, 2015). In the context of ED, the LoS refers to the period between patient arrival and disposition (see Figure 1). For example, Alavi-Moghaddam, Forouzanfar, Alamdari, Shahrami, Kariman, Amini, & Shirvani (2012) applied the QT to study the effect of LoS to changing operational strategies in ED.

ToC is implemented as a concept of maximising output by optimising operation or services (Krajewski, Ritzman, & Malhotra, 2006). ToC has primarily facilitated to resolve bottlenecks in manufacturing, and lately in service industries such as banking (Simsit, Günay, & Vayvay, 2014). Aguilar-Escobar, Garrido-Vega, & González-Zamora (2015) is a more recent work that has applied ToC to alleviate storage and storing bottlenecks in the management of hospital medical records. There is little work that considered the application of ToC in ED. Ahmad, Ghani, Kamil, & Tahar (2010) proposed to apply the approach of ToC to sub-ordinate resources from related services in order to solve conflict of supply and demand in ED. Groop, Reijonsaari, & Lillrank (2011) applied ToC to measure the operational criteria in order to assess how doctors' qualifications affect ED operation.

The processes in ED management can be viewed as discrete events. Discrete Event Simulation (DES) has been applied in ED. For example, DES has been applied to study ambulance diversion to solve overcrowding (Lin, Kao, & Huang, 2015). The issue to relieve overcrowding is also studied by Zeinali, Mahootchi, & Sepehri (2015) through changing the quantity of resources. In Venugopal, Otero, Otero, & Centeno (2012), DES is applied to study how bottlenecks in ED are influenced by changing staffing scenarios.

Agent-based Simulation (ABS) is an alternative simulation paradigm. It shifts the focus of simulation from process-oriented (as in DES) to goal-oriented. In the context of ED, ABS has been applied to better understand staffing and throughput. As an example, Taboada, Cabrera, Iglesias, Epelde, & Luque (2011) used ABS to investigate scenarios of ED staffing that fit patient arrival. Similarly, some of the authors of this paper have previously studied patients LoS in emergency room in the context of re-triage through ABS (Rahmat, Annamalai, Halim & Ahmad, 2013)(Annamalai, Khairani, & Rahmat, 2015).

IV RESEARCH METHOD

Our simulation method follows the six general steps prescribed by Zeltyn, Lauterman, Schwartz, Moskovitch, Tzafrir, Basis, & Shtub (2011).

A. Model Development
B. Model Verification
C. Data Collection
D. Model Integration
E. Model Validation
F. Simulation Analysis

A. Model Development

In this step, the patient flow model that is vital to the understanding of the ED management is developed. The model is completed by listing all the related services in ED, and the connections between them. The service queues that are due to bottlenecks are identified in the model.

The UMMC-ED patient flow model is shown in Figure 1. It shows the main services: patient arrival, triage, management, investigation and disposition. The suffix 'R', 'Y' and 'G' at the end of Management and Disposition distinguishes the services in the Red, Yellow and Green zones, respectively. The asterisked labels refer to services with queue.

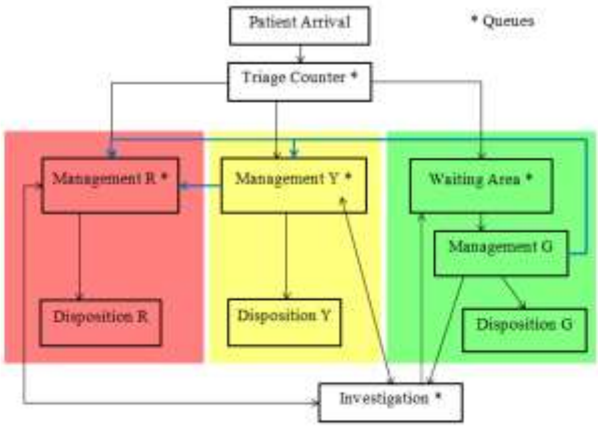

Figure 16. Patient Flow Model

Patient arrival indicates the point when the patient arrives at ED. This is followed by patient registration, which is not shown in the model because it does not contribute to the outcome; the registration of patients is often done by someone other than the patient. The patients will be triaged based on the severity of their health conditions and directed to one of the three zones for management.

Because Red and Yellow zone patients require immediate and urgent medical attention, they are moved to the bed immediately. Yet, there is an implicit priority queue of the arrivals. The Green zone patients queue for their consultation in the waiting area.

The management in ED is performed in blocks of procedures; also known as stages. Each stage comprises three activities: Diagnosis, Treatment and Prognosis. Diagnosis is the procedure to identify the cause of problem or illness by examining the patient. Treatment is a medical or surgical procedure to cure a patient. Prognosis is to predict the outcome of the treatment, which is confirmed through monitoring and/ or investigation that follows. Patients in the Red and Yellow zones undergo up to a maximum of three management stages, after which the case is escalated for intensive care (the stages are not shown in the model). Sometimes critical patients wheeled into the Red zone require resuscitation prior to diagnosis. Resuscitation is included as a part of first management stage.

Investigation is needed when doctor requires certain diagnostic tests to be carried out in the central laboratory to verify or confirm the presence of a disease. There are three main investigations: Blood test, Urine test and Imaging (X-Ray, CT-Scan, MRI, etc). The Blood and Urine tests are normally conducted internally in the Red and Yellow zones. If a Green zone patient is directed to the laboratory, he or she will rejoin the queue in the waiting room for post-investigation management.

The flows in all three zones end with Disposition, i.e., ED exit point. The disposed patient may go home, sent to ward for observation, sent to another hospital for specialised care or sent to the intensive care unit.

Nine queues have been identified in the model (asterisked services): Triage Counter, 1st Stage, 2nd Stage and 3rd Stage Management in the Red zone (waiting for doctor's attention on bed), 1st Stage, 2nd Stage and 3rd Stage Management in the Yellow zone (waiting for doctor's attention on bed), Green Zone (waiting area), and Investigation (waiting to perform Imaging, Urine and Blood tests).

B. Model Verification

The detailed patient flow model is verified in terms of the model details and validated to represent the real-world environment with the help of doctors, and later cross-checked with the administrators in the UMMC-ED. Subsequently, their cooperation is sought for collecting the primary and secondary data with which computer simulation model is constructed.

C. Data Collection and Analysis

The simulation is based on the data collected at a number of points in the ED services shown in Figure 1. The data is collected from two sources, primary and secondary source.

Primary source is data collected manually using time stamping device. Secondary source is data that is extracted from the live emergency medical records generated by the Patient Management System with permission; some were collected from the patient registration logs maintained by the ED administration, while others were obtained from the ED administration reports.

The collected data are cleaned to remove the outliers, and cross-verified before analysing them to produce the probability distributions described in the following subsections. Note that the time units are specified in minutes unless indicated otherwise.

Patient Arrival. We began by investigating the patient arrival at ED on weekdays and weekends, and during different work shifts. The data is collected manually using time stamping device and the sample size is 234. Figure 2 shows four samples of inter-arrival frequencies at UMMC-ED, on weekdays and weekends.

Consequently, we checked the similarity of weekday and weekend patient arrival. We performed a Z-score test on the data, and the P-value is 0.344. Therefore, we can conclude that at $\alpha = 0.05$, there is no significant difference between the arrival patterns on weekdays and weekends.

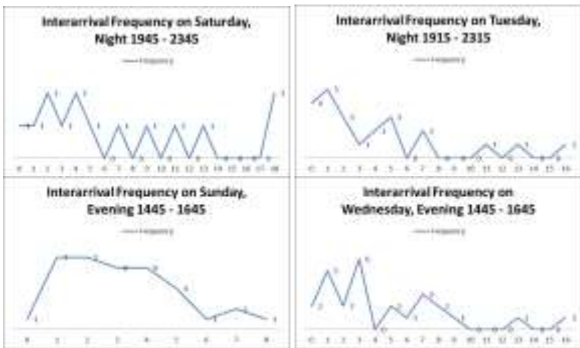

Figure 17. Inter-arrival of Patients at UMMC-ED

The patient arrival follows *Exponential* distribution specified by the function,

$$f(x) = \begin{cases} \frac{1}{m} e^{-x/m}, & x > 0 \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

where x is data value and m is mean; $m = 4.41$

The challenge is to manage the patients during the peak hours. In order to determine the peak hours in ED, the patient registration logs are analysed. The graph in Figure 3 shows the average patient arrival in ED in November 2015 (sample size of 7276). It can be seen that the number of incoming patients rises to 6 patients per hour around 0800 hours (i.e., at the beginning of the morning shift) and remains at or above this limit until midnight. The trend is similar for both weekdays and weekends except for a slight dip around 1800 hours on weekdays. Consequently, we set the range from 0800 to 2400 (16 hours) as the peak hours in this study.

Triage. Patients are triaged according to their severity, and assigned to one of the three zones. We used the patient registration logs to determine the proportion of patients going to red, yellow and green zones. The sample size is 53,291 records, which encompasses the data logged for six months duration, i.e., from March to August 2015. Our analysis shows that 7% of the patients are assigned to the Red zone, 26% to the Yellow zone, and 67% to the Green zones. It can be seen that the number of patients admitted to the Red, Yellow and Green zones are approximately in the ratio of 1 **:** 3.7 **:** 9.6.

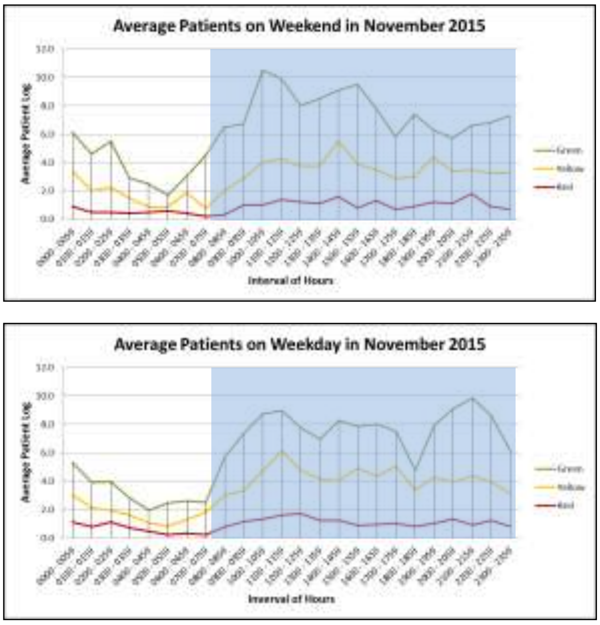

Figure 18. Peak Hours in UMMC-ED (0800 to 2400)

Next, we determine the probability distribution of the time required for triage processing. We analysed the July 2015 triage records; the sample size is 1974 records. The cleaned sample data follows *Beta* distribution, specified by the function,

$$f(x) = \begin{cases} \frac{x^{\beta-1}(1-x)^{\alpha-1}}{B(\beta,\alpha)}, & 0 < x < 1 \\ x, & \text{otherwise} \end{cases} \quad (2)$$

where x is data value, α is shape parameter and β is scale parameter; $\alpha = 1.75$, and $\beta = 1.44$

B in the above function is the complete beta function,

$$B(\beta, \alpha) = \int_0^1 t^{\beta-1}(1-t)^{\alpha-1} dt \quad (3)$$

Management in Red Zone. Patients can go through up to three stages of management in the Red Zone. The sample data is captured from the live emergency medical records (EMR) during the peak hour period (0800 to 2000) over two days, i.e., on 19 August 2015 and 24 September 2015. The sample has 27 records. The probability distribution of the 1st Stage management in the Red zone follows *Weibull* distribution specified by the function,

$$f(x) = \begin{cases} -\alpha\beta^{-\alpha} x^{\alpha-1} e^{-\left(\frac{x}{\beta}\right)^{\alpha}}, & x > 0 \\ 0, & \text{otherwise} \end{cases} \quad (4)$$

where x is data value, α is shape parameter and β is scale parameter; $\alpha = 1.08$ and $\beta = 67.4$

Both the 2nd and the 3rd Stage managements follow *Beta* distribution specified by the probability function given in (2). For the 2nd Stage Management in the Red zone, $\alpha = 0.654$ and $\beta = 0.45$, while for the 3rd Stage Management in the Red zone, $\alpha = 0.371$ and $\beta = 0.558$

Management in Yellow Zone. Like in the Red zone, the patients in the Yellow zone can also go through up to three stages of management. The sample data is captured from the EMR during the peak hour period (0800 to 2300) on 19 August 2015. The sample has 41 records. The probability distribution of the 1st Stage management in the Yellow zone follows the *Weibull* distribution specified by the function described by equation 4, where the shape and scale parameters are $\alpha = 1.34$ and $\beta = 64$, respectively

The 2nd Stage management follows *Triangular* distribution specified by the function,

$$f(x) = \begin{cases} \frac{2(x-a)}{(m-a)(b-a)}, & a \le x \le m \\ \frac{2(b-x)}{(b-a)(b-m)}, & m \le 0 \le b \\ 0, & \text{otherwise} \end{cases} \quad (5)$$

where x is data value; and, *a*, *m* and *b* are the minimum, mode and maximum values, respectively; $a = 18$, $m = 35$, and $b = 154$.

The 3rd Stage management follows *Uniform* distribution specified by the function,

$$f(x) = \begin{cases} \frac{1}{b-a}, & a \le x \le b \\ 0, & \text{otherwise} \end{cases} \quad (6)$$

where x is data value; and, a and b are the minimum and maximum values, respectively. The values of x are between a and b; $a = 37$ and $b = 162$.

Management in Green Zone. Patients in the Green zone go through a single stage management, where the pre- or post-investigation managements are treated alike. The sample data is obtained from the patient registration logs recorded in July 2015. The sample size is 2926 records. The cleaned Green zone management sample data follows *Beta* distribution specified by the probability function given in (2), where the shape and scale parameters are $\alpha = 1.33$ and $\beta = 0.979$, respectively.

Investigation. The investigation data is organised according to the zones (i.e., Green, Yellow and Red) and by the types of investigation (i.e., Imaging, Urine and Blood tests). The sample data is captured from the patient registration logs recorded in July 2015. The sample contains 2676 (Green Imaging), 2285 (Yellow Imaging), 751 (Red Imaging), 1375 (Green Urine) and 474 (Green Blood) records. The Urine and Blood tests are performed internally in the Red and Yellow zones. As in the previous cases, the samples are cleaned to remove the outliers.

The Imaging investigation for Green Zone follows *Exponential* distribution specified by the probability distribution function given in (1), where mean $m = 13.5$

The Imaging investigation for Yellow Zone follows *Gamma* distribution specified by the function,

$$f(x) = \begin{cases} \frac{\beta^{-\alpha} x^{\alpha-1} e^{-x/\beta}}{\Gamma(\alpha)}, & x > 0 \\ 0, & \text{otherwise} \end{cases} \quad (7)$$

Γ in the above function is the complete gamma function,

$$\Gamma(\alpha) = \int_0^\infty t^{\alpha-1} e^{-1} dt \quad (8)$$

where the shape and scale parameters are $\alpha = 1.33$ and $\beta = 1.97$, respectively.

The Imaging investigation for Red Zone also follow *Gamma* distribution specified by the probability function given in (7), where $\alpha = 1.65$ and $\beta = 0.594$

Both the Urine and Blood investigations in the Green zone follow *Log Normal* distribution specified by the function,

$$f(x) = \begin{cases} \frac{1}{\sigma x \sqrt{2\pi}} e^{-(\ln(x)-\mu)^2/(2\sigma^2)}, & x > 0 \\ 0, & \text{otherwise} \end{cases} \quad (9)$$

where x is data value; and μ and σ are the log mean and the standard deviation values, respectively.

For the Urine investigation in the Green zone, $\mu = 9.83$ and $\sigma = 15.9$; while for the Blood investigation, $\mu = 18.7$ and $\sigma = 18.2$

D. Model Integration

The ED management model is implemented in Arena. The ED management services are divided into three zones: Green, Yellow and Red. Each of the zonal services is a sub-model of the integrated management model. The services in the Yellow and Red zones are further subdivided into three stages: 1st, 2nd and 3rd stage managements. Each management stage is a sub-model of the corresponding Red and Yellow sub-models.

We configured the Arena implementation parameters according to the probability distributions described in the previous section. The simulation time period is set from 0800 to 2400, i.e., the during the peak hours. Therefore, the simulation will cover the whole of morning and the evening shifts, but just the first two hours of the overnight shift.

Further, the simulation is governed by the following assumptions:

- Scenario depicts the situation in ED on a normal day, i.e., not while public holiday or during epidemic disaster (when overcrowding is expected).

- Patient will complete the whole journey from arrival at ED to disposition from ED, i.e., there is no 'leave without being seen' incident.
- Doctors will attend to only one patient at any one time, i.e., no doctor may be simultaneously present at more than one patient side.
- A doctor is selected at random to attend to a patient based on their availability at the time of assignment.
- The clinical supervision and training by the specialists and physicians in the Red and Yellow zones are disregarded.
- Laboratory is a central investigation point for investigations related to Blood, Urine and Imaging. It will be manned by two assistants at all time.

E. Model Validation

The model is validated to ensure it has been correctly integrated and configured in Arena. The data used to fit the model is validated against the ED administration's estimates, as well as alternative sample data in hand, which is spelt out in Table 2.

Table 2. Model Validation

ED Service	Validation Data
1. **Patient Arrival**	Patient registration log records
2. **Triage** Average processing time	Observation (samples collected manually using time stamping device) and estimation of triage time by the ED administration
3. **Management R** Average processing time 4. **Management Y** Average processing time	Estimations supplied by the ED administration
5. **Management G** Average processing time 6. **Investigation** Average processing time	Analysis of alternative sample data obtained from the patient registration logs, and the estimations supplied by the ED administration

F. Simulation Analysis

We began the simulation analysis using a default scenario of six (6) doctors per shift, i.e., two doctors allocated to each zone in each shift. Consecutively, we modified the scenario by adding doctors until two predetermined constraints are satisfied, i.e., doctors are maximally utilised and patients waiting time is reasonable. We regard doctors are maximally utilised when they work between 70 and 80 percentages of the time in a shift. Patients waiting time can be considered reasonable if on the average they have to wait no longer than the allowed maximum waiting time to receive attention (as shown in Table 1).

The results of the analysis are summarised in Table 3. In total, seven scenarios have been studied to determine the right allocation of doctors in ED during the peak hours (0800 to 2400) that span over three shifts. The labels AM, PM and ON are abbreviations for the morning (0800 to 1500), evening (1500 to 2200) and the first two hours of the overnight (2200 to 2400) shifts, respectively. The average patient waiting time in the Red and Yellow zones are organised according to their individual 1st, 2nd and 3rd management stages labelled S1, S2 and S3, respectively. The patients' waiting time under each stage is averaged across the simulation period (0800 to 2400).

Table 3. Results of Simulation Analysis

Scenario		Allocated Doctors	Avg. Doctors' Utilisation Rate			Avg. Patients' Waiting Time		
No.	**Zone**		**AM**	**PM**	**ON**	**S1**	**S2**	**S3**
1	**R**	**2**	**64**	**62**	**44**	**17**	**18**	**13**
2	**Y**	2	97	110	100	185	204	145
3		3	93	107	93	76	79	75
4		**4**	**84**	**90**	**57**	**23**	**20**	**19**
5		5	56	49	40	10	10	8
6	**G**	**2**	**72**	**35**	**31**	**6**	NA	NA
7		3	55	11	10	1	NA	NA

V DISCUSSION AND CONCLUSIONS

The results show that the morning and evening shifts are the doctor-critical shifts, which will be the focus in the ensuing discussion. The Yellow zone is the doctor-critical zone in the ED, which is apparent in the number scenarios that are needed to study the allocation of doctors in this zone. The consecutive scenarios also show that the patients' waiting time is more sensitive to the addition of doctors compared to the doctors' utilisation rate.

The default number of two doctors allocated to the Red zone is adequate, yet the doctors appear to be under-utilised in the zone (average utilisation rate around 57%). However, the slack may be justified due to the clinical supervision and training provided by the specialists, which are not taken into consideration in the simulation model. Since the patients should be attended to immediately in the Red zone, the average waiting time (approximately 15 minutes) raises some concern. A probable explanation for the late response by doctors may be attributed to the management of the critical patients in the Red zone. These patients often need to be resuscitated and stabilised by paramedics before attended to by a doctor for diagnose and treatment.

Likewise, the results show that allocation of the default number of two doctors to the Green zone satisfies the predetermined constraints. The average doctor utilisation rate is only slightly above 50%. Even though the number of doctors is just right during the morning shift, their utilisation rates are very low during the evening and night shifts. We also draw attention to the average waiting time of patients in the Green zone, which is only 6 minutes. However, this does not mirror the long queue typically observed in the waiting area. There appears to be considerable time lag between management of consecutive patients in the Green zone. The findings warrant the need for UMMC-ED to review the operating procedure of patient management in the Green zone.

Our results show that at least four doctors need to be allocated to the Yellow zone in order to satisfy the doctors' utilisation rate and patients waiting time constraints. Even though the average utilisation rate is 77%, the high utilisation rate of 87% during the day shifts is unjustifiable especially when the physicians' additional supervisory role has not been taken into consideration in the simulation model. On the other hand, increasing the number of doctors to five is also not acceptable because the addition causes the average utilisation rate of doctors to fall below 50%; and, the waiting time of patients also drop to 10 minutes (much less than the allowed waiting time of 30 minutes). Consequently, we propose to allocate two doctors to the Red and Green zones, and four doctors to the Yellow zone. We plan to deal with the high utilisation rate of doctors in the Yellow zone by repositioning doctors who are free in Red and Green zones for a period of time, particularly during the day shifts. This is slated as our future work.

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