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Application of Discrete Event Simulation and System Dynamics Modeling in Optimizing the Performance of OutPatient Department

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Abstract: This research is aimed to optimize the length of queues and the waiting time of patients at the general OutPatient Department (OPD). A Discrete Event Simulation (DES) model was developed to model the queuing system of OPD and a system dynamics (SD) model was developed to conduct the cost calculations of the OPD. Both models were constructed by using the same data. Since the association of variables, waiting time, number of patients, number of servers at various service channels and opportunity cost, with one another is non-linear, this was the reason the authors used the SD approach for calculations. The present research is a reflection of how the performance of OPDs can be optimized by using the DES and SD modelling techniques. The present research contributes to giving a direction to hospitals to optimize their performance by using the DES and SD modelling and simulation techniques.

Keywords: *queuing system; nonlinear systems; outpatient department; waiting time; length of the queue; Nash equilibrium.*

Mathematics Subject Classification (2010): 81T80, 93C10, 93C65.

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1 Introduction

Hospitals are described as complicated systems with certain benefits that are expensive for the general public [1]. Patient overcrowding in waiting areas, emergency rooms, intensive care units, and outpatient departments (OPDs) is presently one of the hospital's biggest concerns [2]. This is due to the absence of end-to-end queuing system administration in numerous hospital departments [2]. The main issue is the queue, which is unquestionably caused by improper administration of queuing systems [1]. When the number of servers is less than the number of entities to be served in the system, then a queue is formed [3]. Addressing issues regarding health care including resource utilization, epidemiologic concerns, patient flows, and allocation of resources, in DES, has proven to be a reliable tool for healthcare systems [4].

The SD modeling approach is used to model the variables that are non-linearly correlated with one another. Numerous authors have worked on the DES modeling approach and studied patient flows in the clinical setting. Torri et al. [5] studied activities workflow at the Department of Laboratory Medicine of the "San Paolo" Hospital in Naples. Williams et al. [6] used a DES modeling approach for the determination of bed requirements at the critical care unit in the United Kingdom. Melman et al. [7] utilized the DES modeling approach to define the patient flows in emergency surgery and elective surgery during the COVID-19 pandemic. Numerous authors have worked on the optimal allocation of resources in healthcare settings by using DES modeling and simulation; they have worked on the minimization of waiting time [8,9]. Whereas in the present research, the DES and SD modeling approaches were used to evaluate and analyze the current queuing system of the OPD.

In the present research, a queuing system of the OPD of an anonymous hospital was studied and the number of required resources was suggested accordingly to the congestion at the various service channels. Moreover, the Nash equilibrium was used to decide the best scenario analyzed by the DES and SD modeling approaches.

2 Research Methodology

2.1 Data collection

Data collection was the first step of the present research; it included the arrival rate of patients at the OPD and their service rate at the reception and triage; furthermore, the service rate of patients by various doctors available at the OPD was also collected. The second step was the model development in Anylogic software, it was conducted using the DES modeling (see Figure 4) and SD modeling techniques.

The arrival rate of patients was collected as the number of patients who arrived at the OPD per hour. The arrival rate of patients was then put into the custom distribution function of Anylogic software. The service rate of patients at the reception was collected as the time to serve one patient, the service rate was also put into the custom distribution function for various stages of service. Some distribution functions are given below.

Resource pools were used to include the set of resources (receptionists, nurses, various types of doctors) and the parameters were used to initialize the number of the various resources (see Figure 3).

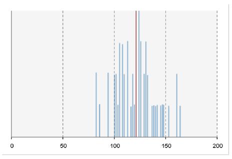

Figure 1: The arrival rate of the patients at the clinic.

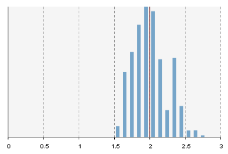

Figure 2: Service rate of patients at reception.

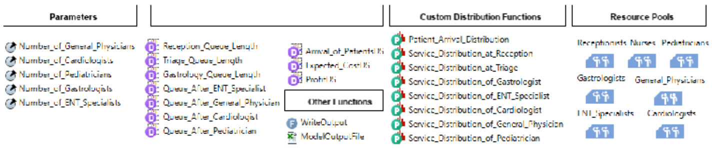

Figure 3: Parameters, datasets, custom distribution functions, and resource pools as used during the model development.

2.2 Model development

2.2.1 Development of DES model

In the gravity of consideration to the discussion in the process workflow of the OPD, the flow of patients, the DES model was developed (see Figure 4). Several elements from the process modeling library were in the model given in Figure 4. The '*Source'* was used for the arrival of patients, and the number of patients arriving at the OPD per hour was already put in the custom distribution function; therefore, the input of the *source* in the model was put to be the '*Patient_Arrival_Distribution*'. After the entrance of the patients into the OPD, their entrance time was noted by using the '*time measure start*' from the process modeling library of Anylogic.

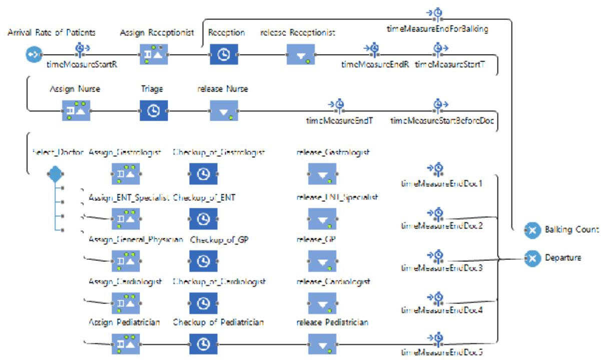

Figure 4: The discrete event simulation model designed in Anylogic.

The receptionist from the resource pool (*Receptionists*) was then seized (*Assign_Receptionist*) at the reception and the queue is formed; the condition was applied to the queue that if the waiting time of the patient in the reception queue exceeds 60 minutes, then he/she balks. The '*Delay'* function (*Reception*) was used to serve the patients at the reception and the service distribution of patients was put to be the '*Ser-*

vice_Distribution_At_Reception' (see Figures 2-3). The total time spent by the patients at the reception (waiting time + reception service time) was calculated by the *'time measure end'* function from the process modeling library. Similarly to reception, the time spent by the patients at various service channels (triage, gastrologists, ENT specialists, cardiologists, pediatricians, and general physicians) was calculated using the '*time measure end*' function. After the patients are served at the reception, then the nurses are seized at triage to serve the patients. As per the data collection, 36.68% of patients visited the OPD for health issues related to gastrology, 12.47% of the patients because of ENT issues, 27.68% of the patients visited the OPD because of issues associated with cardiology, 13.95% of patients visit the OPD because of issues associated with their children; moreover, 9.23% visit the OPD to consult general physicians. After the patients were served from the triage, they were sent to a specific type of doctor as per the nature of their health issue. The decision of sending a particular patient to a specific type of doctor was made based on the above-discussed percentages. At the end of the queuing system, the time spent by the patients in the queue to consult the doctor and the consultation time of patients were recorded. When a patient is served from all the service channels, he/she departed from the OPD.

2.2.2 Development of system dynamics model

The system dynamics model was also developed in the present research. The stock and flow diagram was developed (see Figure 5) using the flow of patients through various service channels. Various distributions used in the DES model were put in the flows of the system dynamics model. The input in the Arrival rate flow was put to be the Patient arrival distribution, the flow, i.e., the service rate at reception was initialized with the distribution function of the service Distribution at reception, the service rate at triage was initialized with the service distribution at triage. The Service distributions of patients by various types of doctors were also put in the same way.

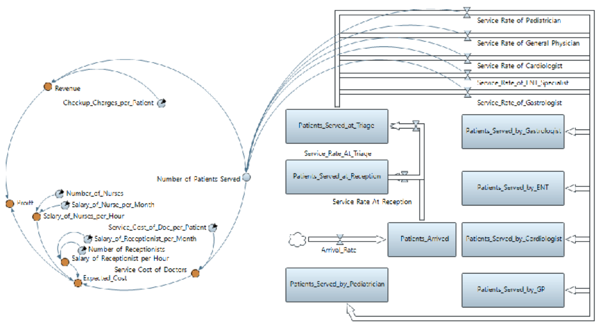

Figure 5: The system dynamics model synchronized with the discrete event model.

The set of equations represents the various stocks used in Figure 5.

$$P_a(t) = \int_{t_0}^{t} \varphi_{ar} dt + P_a(t_0), \tag{1}$$

$$P_{sr}(t) = \int_{t_0}^{t} [\varphi_{ar} - \varphi_{srr}] \, dt + P_{sr}(t_0), \tag{2}$$

$$P_{st}\left(t\right)=\int_{t_0}^{t}\left[\varphi_{srr}-\varphi_{srt}\right]\,dt+P_{st}\left(t_0\right), \tag{3}$$

$$P_{sg}\left(t\right)=\int_{t_0}^{t}\left[\varphi_{srt}-\varphi_{srg}\right]\,dt+P_{sg}\left(t_0\right), \tag{4}$$

$$P_{sent}\left(t\right)=\int_{t_0}^{t}\left[\varphi_{srt}-\varphi_{srent}\right]\,dt+P_{sent}\left(t_0\right), \tag{5}$$

$$P_{sc}\left(t\right)=\int_{t_0}^{t}\left[\varphi_{srt}-\varphi_{src}\right]\,dt+P_{sc}\left(t_0\right), \tag{6}$$

$$P_{sgp}\left(t\right)=\int_{t_0}^{t}\left[\varphi_{srt}-\varphi_{srgp}\right]\,dt+P_{sgp}\left(t_0\right), \tag{7}$$

$$P_{sp}\left(t\right)=\int_{t_0}^{t}\left[\varphi_{srt}-\varphi_{srp}\right]\,dt+P_{sp}\left(t_0\right). \tag{8}$$

The total number of patients served at the OPD was calculated by (9), the cost of receptionists per hour was calculated by (10), (11) was for the calculation of the cost of nurses per hour, the service cost of doctors was calculated by using (12), the total expected cost was calculated by using (13), (14) was for the calculation of revenue, and (15) was for the calculation of profit.

$$N_{ps}=\varphi_{srg}+\varphi_{srent}+\varphi_{src}+\varphi_{srgp}+\varphi_{srp} \tag{9}$$

$$C_{rph}=\frac{C_{rpm}}{D_wT_h}N_{recep}, \tag{10}$$

$$C_{nph}=\frac{C_{nurpm}}{D_wT_h}N_{nur}, \tag{11}$$

$$C_{sd}=N_{ps}C_{sdocpp}, \tag{12}$$

$$C_{ex}=C_{rph}+C_{nph}+C_{sd}, \tag{13}$$

$$R=N_{ps}C_{check}, \tag{14}$$

$$P=(R-C_{ex}). \tag{15}$$

2.3 Model initialization

The DES model was initialized in two scenarios as given in Figure 6. Scenario 1 represents the present situation of the OPD and Scenario 2 is the suggested situation for the OPD. Since the performance of the OPD was based on the number of resources and length of the queue after each human resource (receptionist, nurse, gastrologist, ENT specialist, cardiologist, pediatrician, and general physician), it was dependent on the availability of the number of human resources. The discussion model initialization was applied to both models because they are integrated.

3 Results and Discussions

Under this heading, the results of the present situation of the OPD were discussed and after increasing the number of several resources, the queue length and various other parameters were discussed in detail.

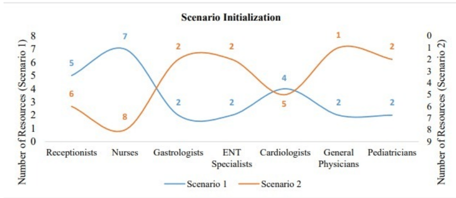

Figure 6: Initialization of the DES model.

3.1 Arrival rate of patients

The arrival rate of patients as indicated by Figure 7 was taken from the output of the flow, i.e., the '*Arrival_Rate*' of the system dynamics model given in Figure 5. A look at Figure 7 indicates that the arrival rate of patients at the OPD was between 80 to 165 patients per hour, which means that this number of patients arrives at the reception and passed through all the service channels. Note: the x-axis of the figure indicates the model

Figure 7: The arrival rate of patients obtained after simulating the SD model.

time in hours and the y-axis indicates the number of patients arriving at the OPD.

3.1.1 Results of Scenario 1

The main problem at the OPD was the congestion of the patients at every service channel. At the reception, even after the availability of 5 receptionists, the queue length of the patients mostly fluctuates between 5 to 10 patients; at one point, the queue length at reception reached 18 patients as indicated by Figure 8. According to the simulation results from Anylogic software, the patients spent an average time of 0.053 hours at the reception including waiting time in the queue and service time of the receptionist. Furthermore, the minimum and maximum time of patients at the reception was taken out to be 0.196 hours and 0.026 hours, respectively. In the existing scenario (Scenario 1), the headcount of nurses was 7 and the queue length of triage indicates that around 10 to 20 patients were in the queue in 382 simulated hours of the OPD, and sometimes even more patients wait in the queue; at one point, the simulation results (see Figure 8) indicate around 45 people in the queue of triage. Furthermore, according to the simulation results, the patients spent an average time of 0.089 hours at the triage including waiting time in the queue and service time of the nurse. The minimum and maximum time of patients

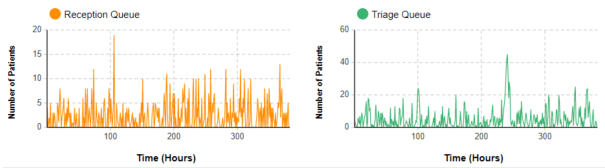

Figure 8: Length of queue at reception and triage.

at the triage was 0.402 hours and 0.035 hours respectively.

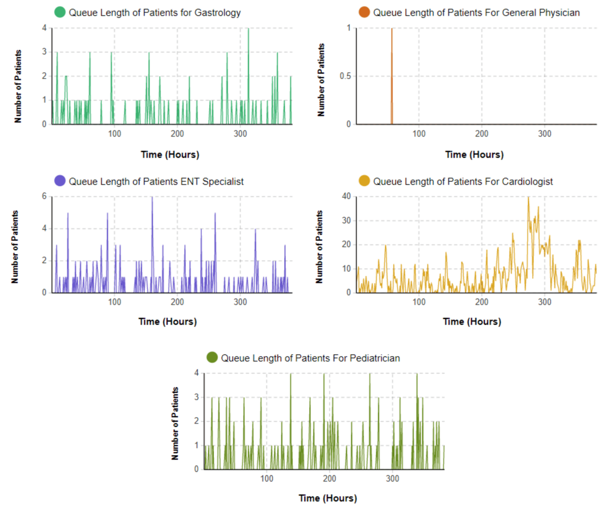

Figure 9: Length of the queue for various types of doctors.

Five types of doctors were available at the OPD. In the existing scenario (Scenario 1), the queue of patients who came to consult gastrologists contained 3 patients on average throughout the simulation time. Similarly, the queues for the ENT specialists and pediatricians are short, which indicates that enough doctors (gastrologits, ENT Specialists, and pediatricians) were there to provide the consultation to the patients. The patients spent an average of 0.032 hours, a maximum time of 0.124 hours, and a minimum of 0.02 hours only to consult a gastrologist; the time spent by the patients to consult an ENT specialist (average = 0.1 hours, minimum = 0.063 hours, and maximum = 0.436 hours) and pediatrician (average = 0.092 hours, minimum = 0.052 hours, and maximum = 0.386 hours) was quite less; this is the reason the queue length for the mentioned doctors was significantly short as given in Figure 9

The queue length for general physicians indicated that as per the flow of patients arriving at the OPD to consult general physicians, the availability of doctors was larger than the requirement. The patients spent an average of 0.036 hours. The time of patients (waiting time in the queue to see a general physician plus the consultation time) indicates that the patients got free quickly from the cabins of general physicians. In this regard, the authors suggested decreasing the number of general physicians as per the current workload. Furthermore, the queue length for cardiologists indicates that the availability of doctors was less than the requirement as per the flow of patients arriving at the OPD to consult cardiologists; this is the reason the queue gets long and patients wait longer to see the doctor. The patients spent 0.29 hours on average, 0.083 hours minimally, and 1.197 hours maximally consulting the cardiologists. The waiting time of patients in the queue and the doctors consultation time were significantly greater as compared to those for the rest of the doctors, this is the reason for the long queue after cardiologists.

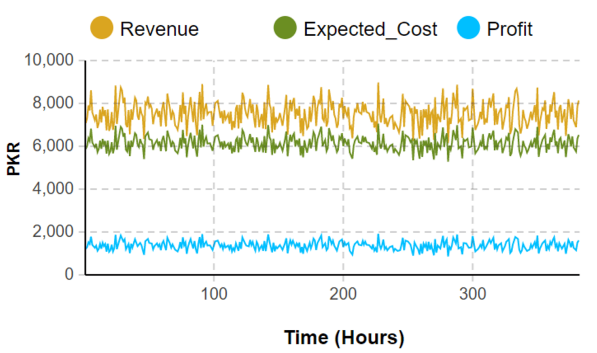

Figure 10: The expected cost, revenues, and profits of the OPD in Scenario 1.

With 5 receptionists, 7 nurses, and 12 doctors, the expected cost, revenues, and profits can be noticed as given in Figure 10. The average expected cost (calculated from the downloaded data into Microsoft Excel), revenue, and profit were calculated to be PKR 61.06.71, PKR 7479.68, and PKR 1362.86, respectively. Moreover, the waiting cost of patients was calculated to be PKR 77.96.

3.2 Results of Scenario 2

The queue length at reception and triage was found to be greater in Scenario 1 as indicated by Figure 14. The authors suggested an increase in the number of receptionists and nurses. In this regard, the numbers of one receptionist and one nurse were increased in Scenario 2 and the DES model was simulated; the results of the simulation are presented in Figure 11 in terms of the queue length at reception and triage.

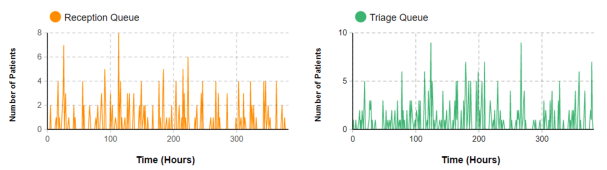

Figure 11: Length of queue at reception and triage.

The length of the queue at reception decreased from 10 to 15 patients to 4 to 6 patients (see Figure 11). Moreover, the patients spent 0.038 hours on average, their minimum time was 0.026 hours, and their maximum time was 0.105 hours. The average time of patients spent at reception decreased from 0.053 hours (Scenario 1) to 0.038 hours (Scenario 2). The length of the queue at triage decreased from 10 to 20 patients to 5 to 9 patients (see Figure 11). Moreover, the patients spent 0.057 hours on average, their minimum time was 0.035 hours, and their maximum time was 0.162 hours. The average time of patients spent at triage decreased from 0.089 hours (Scenario 1) to 0.057 hours (Scenario 2). The maximum time of patients at triage also decreased significantly from 0.402 hours (Scenario 1) to 0.162 hours (Scenario 2). Increasing of the numbers of one receptionist and one nurse increased the service rate of both service channels significantly. The number of general physicians decreased from 2 to 1 and the number of cardiologists increased from 4 to 5 in Scenario 2; this suggestion was made considering the length of the queue for both types of doctors. The queue length for the general physicians was very short, therefore, the number of doctors was reduced and the number of cardiologists was increased because of the greater length of the queue of patients. In Scenario 2, there are some patients in the queue (see Figure 12), whereas, in Scenario 1, the queue length was either 0 or 1, which means the general physicians were under-utilized. The patient's time incurred in the queue for general physicians and the time incurred in the consultation increased (average = 0.047 hours, minimum = 0.026 hours, and maximum = 0.214 hours) as compared to Scenario 1.

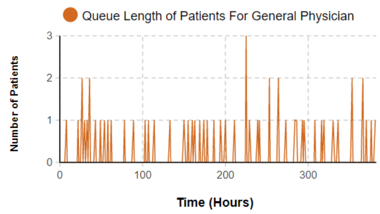

Figure 12: Length of the queue for general physicians after decreasing by one doctor.

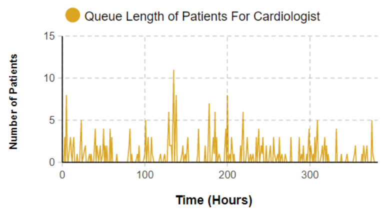

Figure 13: Length of the queue for cardiologists after increasing the number of one doctor.

The length of the queue for cardiologists decreased from 10 to 20 patients to 4 to 10 patients (see Figure 13). Since the number of doctors increased, the system time of patients at the service channel decreased significantly. The patients spent 0.123 hours (instead of 0.29 hours) on average, their minimum time was 0.083 hours, and their maximum time was 0.365 hours (instead of 1.197 hours). The average time of patients spent seeing a cardiologist decreased by 57.58% in Scenario 2 just by increasing the number of one cardiologist.

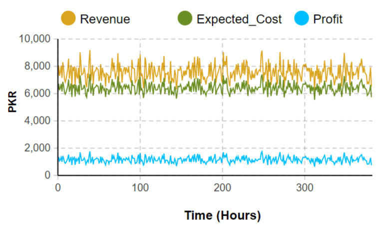

Figure 14: The expected cost, revenues, and profits of the OPD in Scenario 2.

The variation in the expected cost, revenues, and profits were noticed as given in Figure 14. The average expected cost (calculated from the downloaded data into Microsoft Excel), revenue, and profit were calculated to be PKR 6350.60, PKR 7454.67, and PKR 1123.88, respectively. The average opportunity cost of a patient in Scenario 2 was calculated to be PKR 39.90.

4 Calculation of Nash Equilibrium

We summarize the possible metaphorical or analogical transpositions from game theory to the strategic OPD model from the five fundamental concepts of game theory (see Table 4). Player strategies are defined based on payment functions. It is from the expected gains, and taking into account the expected gains of other players. The player examines the consequences attached to the system of possibilities, consequences that do not depend solely on his own decisions. The equilibrium is a situation where everyone's expectations are realized [10].

Concept of game theory	Useful transposition to the strategic OPD model
strategy	Scenarios 1 and 2
decision tree	Concept of bifurcation
players	Patients
payment functions	Taking into account the advantages of other patients
Equilibrium	the notion of indeterminacy causing instability. the result of the strategy is random

Table 3: Concepts of Game Theory.

4.1 Discussion of equilibrium in the OPD model

Let us discuss the Nash equilibrium for 2 patients and which will be generalized for n patients, we will study the Nash equilibrium according to the cost and waiting time, it is in our interest to minimize it, according to Scenario 1 (S_1) and Scenario 2 (S_2) described in this paper. For Scenario 2 (suggested situation of the OPD), the cost of service increases, but the waiting time of the patients decreases and this is the major interest of patients. According to the cost, we have $C_2 > C_1$, where C_i is the patient service cost according to the scenario i; $i = 1, 2$, the different situations are given in Table 4. The Nash equilibrium i is $(C_1\ , C_1)$, it is clear that if, for example, patient 1 follows the scenario S_2 and patient 2 follows S_1, patient 1 can follow S_1 in order to minimize the service cost, so $(C_2\ , C_1)$ is not a Nash equilibrium.

		patient2	patient2
		S_1	S_2
Patient 1	S_1	(C_1, C_1)	(C_1, C_2)
Patient 1	S_2	(C_2, C_1)	(C_2, C_2)

Table 4: Cost matrix of both scenarios.

If we consider now the waiting time of patients T_i, $i = 1, 2\ , T_2 < T_1$, we obtain the following. By the same methodology, the Nash equilibrium is $(T_2\ , T_2)$, we conclude that the Nash equilibrium confirms the results of the two scenarios and we can generalize it for n patients.

		patient2	patient2
		S_1	S_2
patient 1	S1	(T_1, T_1)	(T_1, T_2)
patient 1	S2	(T_2, T_1)	(T_2, T_2)

Table 5: Waiting time matrix of both scenarios.

4.2 Price of anarchy

The price of anarchy is a concept in algorithmic game theory that measures how far a system where all agents act to optimize their interests can be from an optimal situation from the global point of view. We define in our model a set of n patients, two strategies (2 scenarios), and utilities $U_i : S \to$ R, where $S = S_1 \times S_2$. We can define a measure of the efficiency of each outcome which we call a welfare function $W : S \to$ R, $W(s) = \sum_{i \in N} U_i(S)$. We can define a subset $Equils \subseteq S$ to be the set of strategies in equilibrium. If, instead of a welfare which we want to maximize, the function measure of efficiency is a cost function $Cost : S \to R$ which we want to minimize, then

$$P_0A = \frac{\max_{s \in Equil} Cost\,(s)}{\min_{s \in S} Cost(s)}. \tag{16}$$

According to the table of costs defined above, the cost function is

$$C\,(S_1, S_2) = u_1\,(S_1, S_2) + u_2\,(S_1, S_2)\,. \tag{17}$$

The worst (and the only) Nash equilibrium will be when both patients follow S_2 and the resulting cost is $C_{equil} = 2C_2$ as calculated by (18). However, the highest social welfare occurs when both patients follow S_1 , in this case, the cost is $C_{min} = 2C_1$. Thus the P_0A in this situation will be

$$C_{Equil}/C_{min} \ = C_2/C_1. \tag{18}$$

If, instead of a welfare which we want to maximize, the function measure of efficiency is a waiting time function $T : S \to R$ which we want to minimize, the worst Nash equilibrium will be when both patients follow S_1 and the result is $T_{equil} = 2C_1$. In this case, P_0A=C_1/C_2. We have studied an OPD situation with two scenarios for which we calculated the equilibrium and the price of anarchy for the two scenarios and for two patients, something that can be generalized for n patients.

5 Conclusion

At the selected OPD, the queue used to be longer at the reception and triage and cardiologists, whereas it was shorter for the general physicians. Due to the long queues, the system time of patients was longer and they led the OPD to be congested with patients. In this regard, the numbers of one receptionist, one nurse, and one cardiologist were suggested to be increased. Furthermore, due to the short queue of patients to general physicians, one general physician was reduced. The results of the simulation indicated a significant drop in the waiting time of patients in the system and optimization of the length of the queues at the various service channels of the OPD by using the DES. The SD and DES techniques helped researchers to conduct an in-depth analysis of OPD's current situation and the way it can be optimised at a quite reasonable cost. The present research contributes to providing substantial guidelines to hospital management to optimize OPD's performance.

Appendix P_a *(t)* = Patients Arrived, P_{sr} *(t)* = Patients Served at Reception, P_{st} *(t)* = Patients Served at Triage, P_{sg} *(t)* = Patients Served by Gastrologis, P_{sent} *(t)* = Patients Served by EN, P_{sc} *(t)* = Patients Served by Cardiologist, P_{sgp} *(t)* = Patients Served by General Physician, P_{sp} *(t)* = Patients Served by Pediatrician.φ_{ar} = Arrival Rate, φ_{srr} = Service Rate at reception, φ_{srt} = Service Rate at Triage,φ_{srg} = Service Rate of Gastrologist, φ_{srent} = Service Rate of ENT Specialist, φ_{src} = Service Rate of Cardiologis, φ_{srgp} = Service Rate of General Physician, φ_{srp} = Service Rate of Pediatrician. N_{ps} = Number of Patients Served, C_{rph} = Salary of Receptionist per Hour, C_{nph} = Salary of Nurse per Hour, C_{sd} = Service Cost of Doctors, C_{ex} = Expected Cost,R = Revenue, P = Profit. N_{recep} = Number of Receptionists, N_{nur} = Number of Nurses, C_{rpm} = Salary of Receptionist per Month, C_{nurpm} = Salary of Nurse per Month, C_{sdocpp} = Service Cost of Doctor per Patient, C_{check} = Checkup Charges per Patient. D_w = Working Days, T_h = Working Hours.

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