Modelling and Simulating the Processes of an Accident and Emergency Department

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Abstract

An Emergency Department is a complex system characterized by a high variability, depending on random patient arrivals and diversity of required service.
In this context, Simulation can be considered a useful means to understand, analyze and manage the system in order to guarantee acceptable quality of the services.
The presented simulation model reproduces the work processes of one of the largest Accident and Emergency Department (AED) in Rome. Building the model with the software *Simul8* has given the possibility to find out some critical points of the service, which cause long waiting time and an overload of resources in some activities, and to suggest possible alternative solutions.

1. Introduction

The Emergency Health Services (EHS) in the city of Rome are challenged by the need to supply fast and effective medical care to a high - and sometimes exceptional - number of people.
The EHS consist of two different connected phases:

- the phase of the alarm, tackled by the *Centrale operativa 118*, that is contacted by dialling the telephone number 118;
- the phase of the health care, supplied by the Accident and Emergency Department (AED) of a hospital according to the needs and the urgency of the case.

The first phase has been the object of research work [De04], especially during the Jubilee Year 2000, aiming at planning the number and the location of the ambulances and the staff in order to guarantee that a patient reaches the nearest Emergency Department within eight minutes.
Nowadays the attention is focused on the AEDs which are characterized by an ever growing demand due to the typical behaviour of the modern life: the increase of road, labour and domestic accidents, as well as the need to solve urgently also little health problems. Indeed, AEDs have always received attention among the OR community all over the world [Lat04], [Lu87] and [Ro87].
This work refers to the study of one of the biggest AED in Rome, the one situated in the San Camillo-Forlanini Hospital, in order to understand and analyse, through a simulation model, how it works in a normal situation and which are the critical points in terms of resources load and waiting time.
Health Care Service has been object of OR studies [Ut03] and [Vi94], and Simulation has often been a valid tool of analysis [Bo00], [De03], [Fr00], [Fa03], [Lag04], [Ra05] and [Vi99].
The paper is structured as follows: after the problem definition in Section 2, the structure of the San Camillo AED is described in Section 3. Then, in Sections 4-7 the various phases of the simulation study are presented (Collection, Analysis and Elaboration of data; Construction of a logical-mathematical-statistical model; Construction of the Simulation Model by means of a commercial software; Validation, Experimentation and Results Analysis). Finally, in Section 8, the conclusions are exposed.

2. Problem definition

The direct observation of the processes of the San Camillo AED and the several meetings with the medical and paramedical staff have brought to a good understanding of the entire system and to the construction of the different paths followed by the patients according to the urgency codes given them in the Triage: Red and Yellow codes for major patients, Green and White codes for minor patients.
It has been possible to identify the crucial variables on which to focus the attention: arrival rates of patients, activity durations and resources availability, and to set the objective of our study. It has been decided to calculate waiting times, resources utilization, queues length and time spent in the system, in order to identify the bottlenecks of the system and to propose different scenarios.

3. The San Camillo AED

The San Camillo AED area consists of:

- different rooms for general medical examinations of patients according to the different levels of urgency (as we can see from the Figure 1, major patients receive service in the Emergency room located in front of the entry of the AED in order to be attended immediately, while minor patients are examined in rooms located farther away);
- a common area used for the instrumental tests (X-Ray, CAT and Scan);
- different rooms for examinations performed by specialist doctors like orthopaedists, ophthalmologists, heart specialists, ear specialists and surgeons.

As staff is concerned, nurses and most specialist doctors are permanently assigned to the AED, while other specialist doctors are called from the different hospital departments when needed.

4. Data analysis

4.1 Data collection

The data related to the AED activities are managed by GIPSE (*Gestione Informazioni Pronto Soccorso ed Emergenza*), the information system of *Regione Lazio*, the area that includes the city of Rome. GIPSE is accessed at two levels: at the first one, only aggregated data are shown, at the second one, data taken from hospital files are made available. Due to the bureaucratic problems connected with the law on the privacy and to the practical difficulties caused by the software rigidity, it has been possible to obtain information only of the first type.

The system has been questioned in order to obtain for each month, from January 2003 to June 2004 (the AED organization changed a lot in January 2003, making previous data of no interest), information related to the different ways of accessing the AED, to the waiting times, to the specialist examinations and to the instrumental tests, to the bed occupancy and to the result

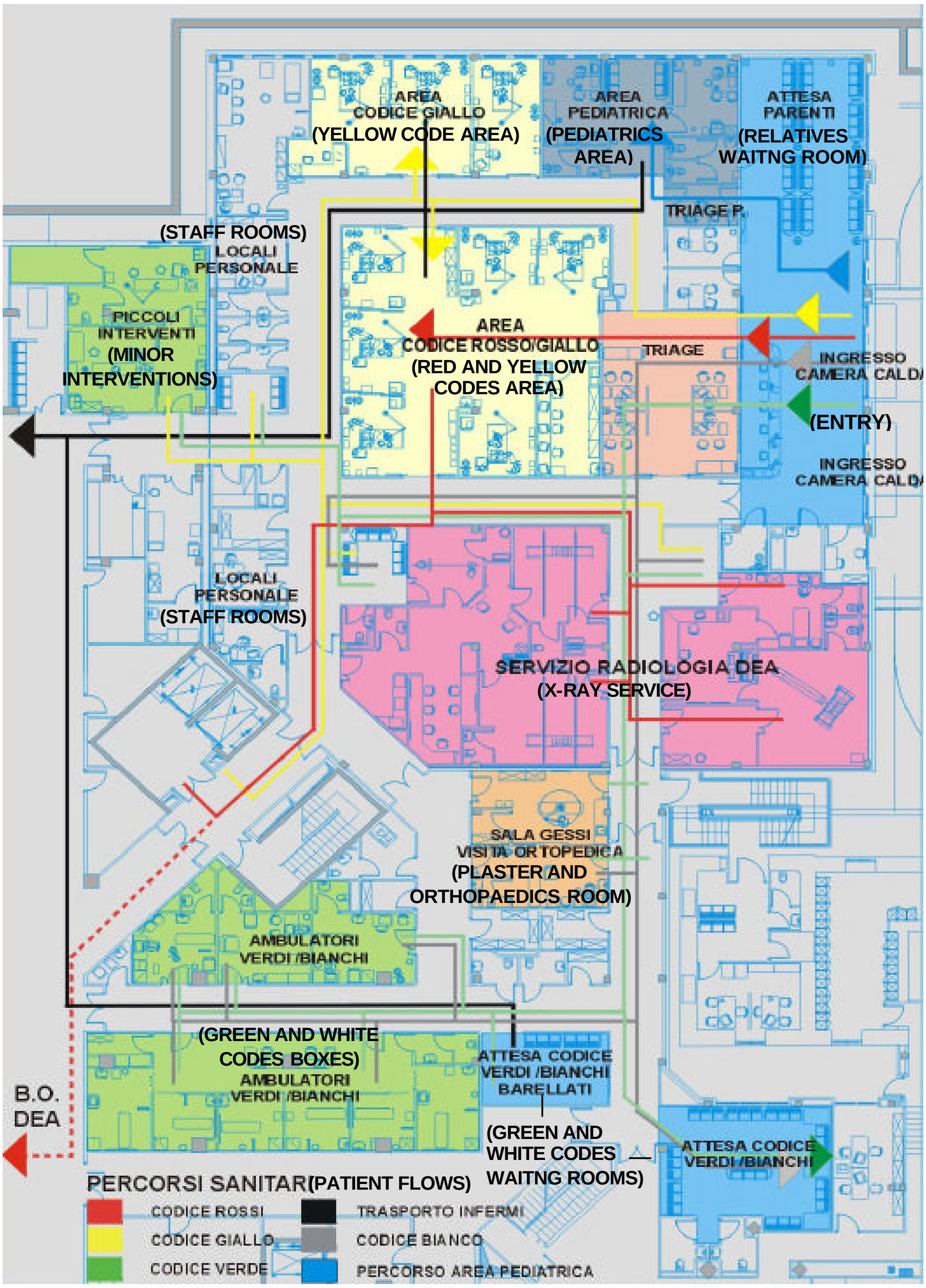


Figure 1. AED plan.

of the treatment of patients classified according to their code. It has not been possible, however, to follow the complete path of each patient and this has partly conditioned our study. Besides, it has been necessary to interview doctors to have some information, for example on activity durations, not available from GIPSE.

4.2 Data elaboration

Data have been recorded in spreadsheets, then elaborated through the *Excel* software.
A first analysis has been performed in order to find whether the distribution of the arrivals to the AED classified by code, month, day of the week and time window of the arrivals is uniform. We have used the non parametrical test ?^{2}, which has been significant only within two particular groups of months (Fig. 2): hot months, with the highest arrival rate of patients, and cold months, with the lowest arrival rate of patients.

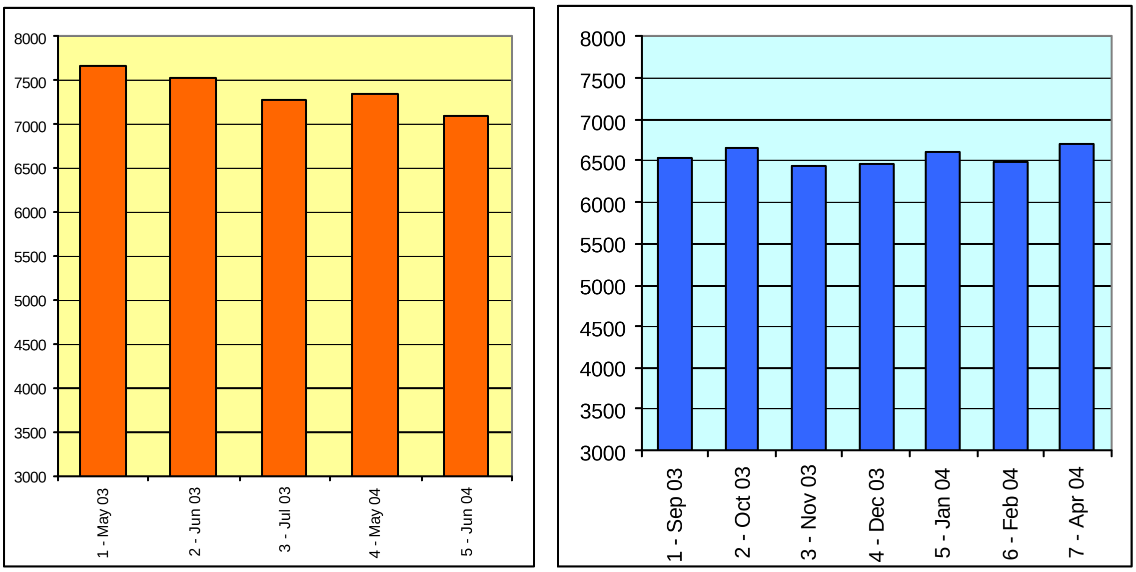


Figure 2. Arrivals in hot and cold months.

A second analysis has verified the independence between various couples of variables by using the test ?^{2}. For example we have verified that the percentage of the monthly arrivals by day of the week does not vary in the different months (Monday is the day with the maximum number of arrivals and Sunday is the day with the minimum number in all months). We have obtained the same result for the percentage of the monthly arrivals in each different time window of 4 hours (the time band from 8 am to 12 am is the one with the maximum number of arrivals and the time window from 4 am to 8 am is the one with the minimum number of arrivals in all months). But the most important result of this analysis shows that the percentages of the four codes are the same for the various months, days of the week and time windows (Fig. 3).

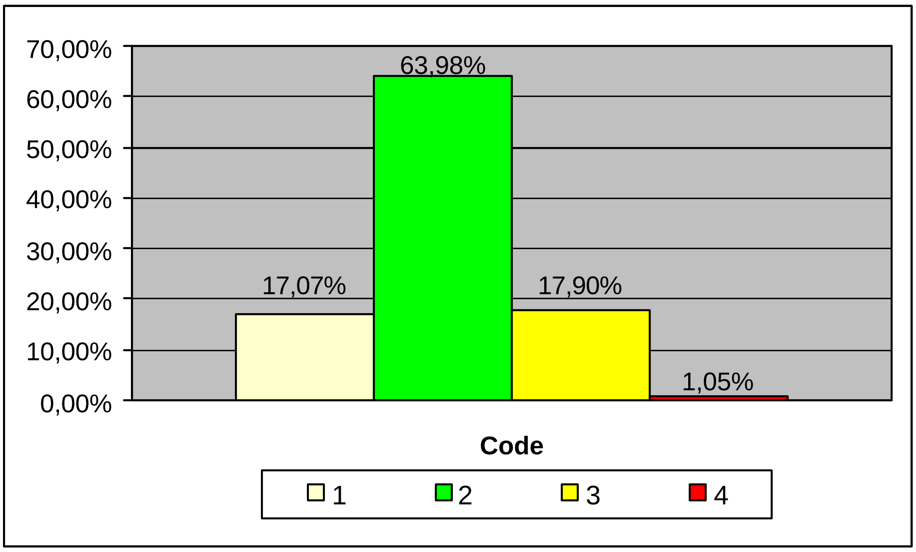


Figure 3. Probability Distribution of Codes.

Thanks to these analysis, it has been possible to calculate probabilities related to the different branches of the various paths of patients, that do not vary with time.

Then we have paid particular attention to the choice of the probability distribution from which to sample the interarrival time and the activity durations for the simulation [Mo88].

For the interarrival time, we have chosen the *Negative Exponential Distribution* with different means calculated from the available data according to the day of the week and the time window (Tab. 1).

For the activity durations we have chosen the *Weibull Distribution*, on the base of the information given us by the doctors about the modal, the maximum and the minimum values. This distribution is very flexible and allows to represent different real situations by modifying the values of scale and shape parameters.

The pictures show in fact that the Weibull can be used to represent the duration, both of activities like the reception (Fig. 4), more concentrated around the modal value (in this case 4 minutes), and of activities like the scan (Fig. 5), which is more variable (in this example from 10 to 40 minutes).

Mean of the esponential distribution for the hot months						
Time windows **Day**	**1. 0-4**	**2. 4-8**	**3. 8-12**	**4. 12-16**	**5. 16-20**	**6. 20-24**
1 – Monday	15,14	16,36	3,54	3,87	4,05	5,42
2 – Tuesday	16,21	17,52	3,79	4,14	4,33	5,80
3 – Wednesday	15,68	16,94	3,66	4,01	4,19	5,61
4 – Thursday	16,23	17,54	3,79	4,15	4,34	5,81
5 – Friday	16,53	17,86	3,86	4,22	4,42	5,92
6 – Saturday	16,71	18,05	3,90	4,27	4,47	5,98
7 – Sunday	20,35	22,00	4,75	5,20	5,44	7,29

Table 1. Average interarrival times according to the day of the week and the time window

Finally, to sample the variables "number of specialist examinations" and "number of instrumental tests" we have chosen the *Poisson Distribution* with mean equal to the average number of specialist examinations or of instrumental tests for each patient, calculated from the data.

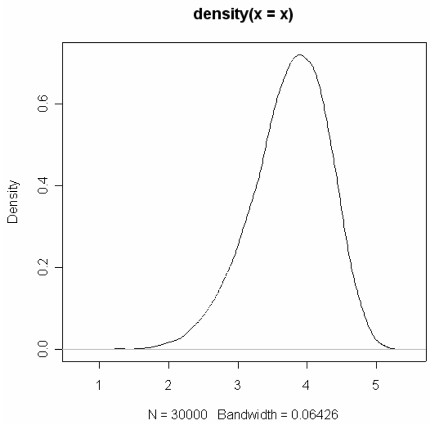


Figure 4. Weibull (a=7,87; ß=3,98).

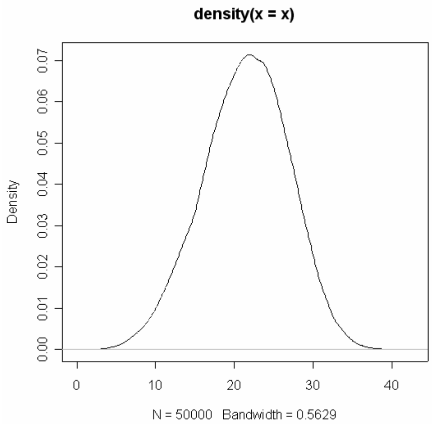


Figure 5. Weibull (a=4,46; ß=23,5).

5. Construction of the logical-mathematical-statistical model

We have built the model representing how the system works. The elements of the model do not have a one-to-one correspondence with the elements of the real system, but they can capture the essence of the system with enough details for the purposes for which the model is intended [Law82].

We had to introduce some hypotheses in order to model the sequence of the medical examinations and the instrumental tests. First of all, the patient receives a general examination called "first medical examination", then we assumed that he/she receives all the specialist examinations first and then the instrumental tests required by the doctor of the first medical examination. Finally, this doctor intervenes again and, after having examined all the test results, closes the hospital file of the patient in the "second medical examination" and sends him/her to his/her final destination (admission to a ward or discharge). Actually the events do not take place necessarily in this order but, considering a general analysis of the processes, such hypotheses do not interfere with the results.

Figure 6 shows the life cycle of the entities (patients) and the functional relationships between the objects of the system. As it can be noticed, there are different paths for the different codes, except for the White code, whose flow is the same as the Green one, since in an AED such patients follow the same path and use the same resources.

While for patients with a Red code the access to the first medical examination is immediate, the other patients must undergo a preliminary test, the Triage, and, if they have Green or White codes and do not arrive by ambulance, also the Reception.

Major patients are visited in the emergency room while minor patients are visited either in the medical or the surgical or the orthopaedic room, depending on their pathology.

After the first medical examination, the patient is given a label showing the number of the specialists he/she needs to see. If such number is greater than zero, the patient will join, according to the probabilities given, one of the queues (with priority by emergency code) corresponding to the different specialists, who, as mentioned before, can be either permanent AED staff or staff called from the other hospital departments to work temporarily in the AED. When the specialist examinations finish (or when the label value is zero), another label showing the number of instrumental tests to be done is given to the patient. Also in this case, he/she will stand in one of the queues for the instrumental tests, chosen according to the probability distribution. X-Ray, CAT and Scan are performed inside the AED, while all the other tests, called External tests, are performed in other hospital departments. When the patient finishes all the tests, he/she receives the second examination, in which the doctor decides where he/she will go from the AED.

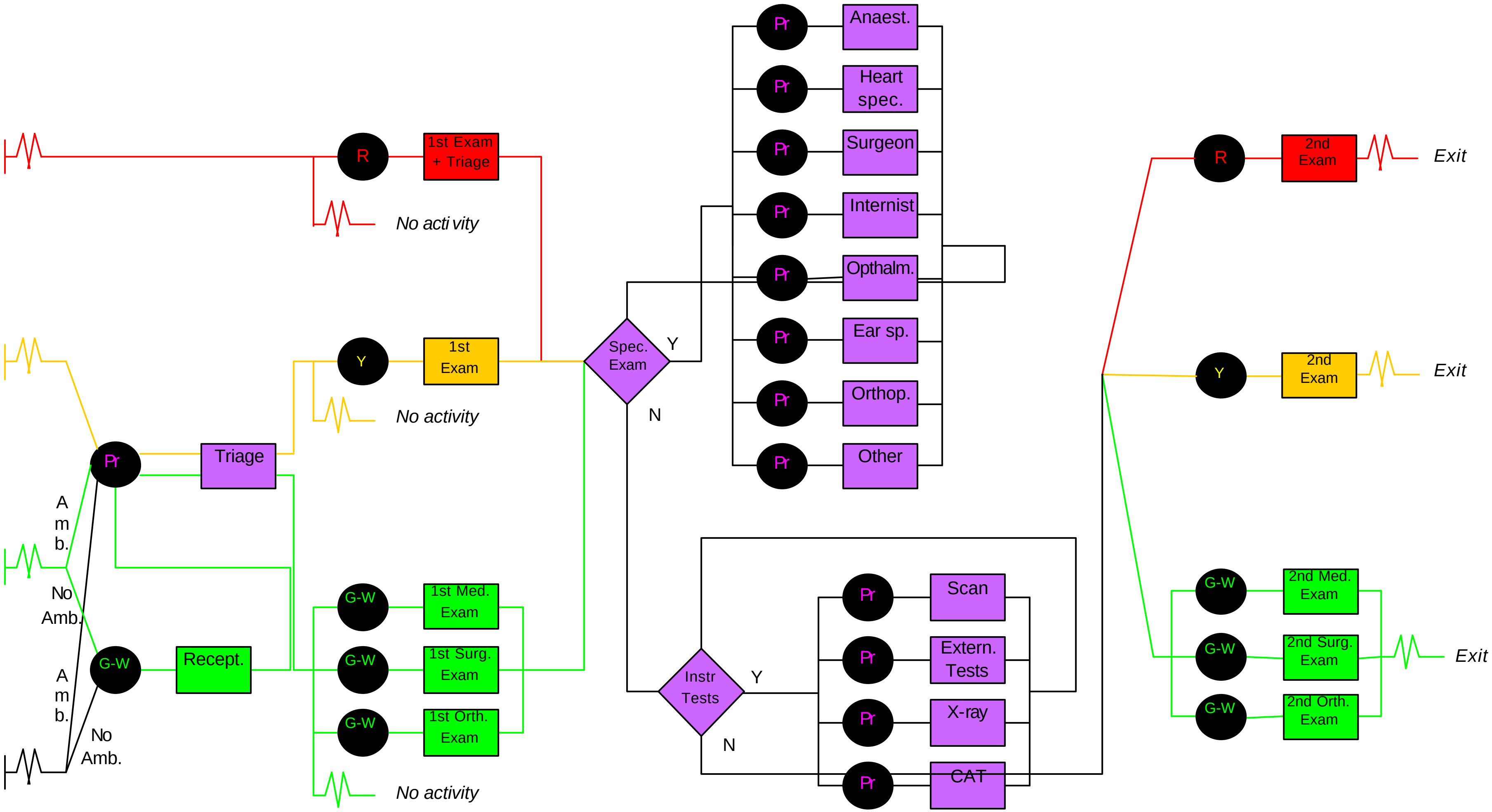


Figure 6. The Activity Flow Diagram.

6. Construction of the Simulation Model

Once drawn the Activity Flow Diagram, we have built a Discrete Event Simulation model using the commercial software *Simul8* of the "SIMUL8 Corporation". It is a software characterized by a high flexibility and simplicity of use, which allows to build the model by means of icons. The base elements - work item, label, work entry point, storage bin, work center, resource and work exit point - have dialogue boxes. Thanks to them it is possible to specify the element characteristics necessary to represent the objects of the real system in the best way. Moreover, the use of the internal programming language *Visual Basic* allows to include in the model more complex logical relations.

In the simulation model there are 60 activities, 24 of which correspond to the real activities of the AED while the others are zero-time activities introduced in order to assign labels that determine the following path. There are also 29 different type of resources - general doctors, specialist doctors, nurses, technicians and beds - which can be *dedicated* to a single activity or *floating* to more activities.

When the simulation starts, the arrivals are originated by a single entry point, after which the item paths differentiate according to the code received on the basis of the probability distribution defined before.

Once in the system, the items follow paths as similar as possible to the paths of the patients in the AED; for example, major patients have the priority in all the queues in common with the minor patients.

In the model there are more than one exit points: the final one that represents the admission to a ward or the discharge of the patient and the ones in proximity of the queues that reproduce the possible real situation in which the generally minor patients give up to be visited because of the long wait.

The choice of the initial conditions, as well as of the length of each run and of the number of independent runs to do, has been fundamental. The duration of each repetition has been fixed quite long, so that all the events, also the most improbable, may happen with acceptable frequency and the first observations, more influenced from the starting situation in which the system is empty, may not be considered in the results [Pi98]. In particular, we have chosen a period of 45 days to study, so as, by neglecting the initial interval of 14 days, we could obtain results relative to a month of simulation, easily comparable with the available monthly data.

Considering the great variability of the model, it has been necessary to perform a great number of repetitions, in order to obtain a good level of accuracy in the results. We have decided to run 100 iterations of the simulation since the results did not change significantly with more repetitions while, with less iterations, we ran the risk to give much importance to extreme situations, deriving from particular sampling of data from the distributions within the model.

7. Validation, Experimentation and Results

Validation has taken place during the whole study in two ways. Indeed, the continuous interaction with the AED staff has always confirmed the adequate representation of the actual processes by the simulation as well as the consistency of the obtained results. This, together with the comprehensive statistical analysis carried out on the data and on the results of both the trial and the final runs, has made us confident of having obtained a valid and complete model. In this context, the results related to the waiting times in the queues confirm that Red code patients always wait few minutes while the waiting time for White code patients is high, especially in those activities most required in the AED.

Moreover, we have verified the model validity on the basis of the value of the whole time spent in the system, which is the only measure of performance of the real system obtainable from the GIPSE. Such value, of about 141 minutes, falls inside the 95% confidence interval of (121.13 – 171,96) minutes, calculated from the simulation, and this confirms again a good level of fit of the model.

Finally, we have carried out the phase of experimentation. During this phase, bottlenecks have been identified and alternative scenarios have been formulated. We have focused on the hot months, when, being higher the number of accesses, critical situations may appear with higher frequency and the elaboration of plans for their solution is more necessary.

The analyses have concerned not only the whole time spent in the system, but also the resources utilization and the waiting times.

Table 2 shows some performance measures of the utilization of the different categories of doctors working in the AED. The percentages of the utilization time for the radiologist dedicated to CAT and for the orthopaedist are the highest ones.

MEDICAL RESOURCES	Utilization Time %	Average Use	Maximum Use	Maximum Availability
RES_Radiologists CAT_Scan	**69,48**	1,04	2	2
RES_Orthopaedist	**68,73**	0,69	1	1
RES_Radiologists X-ray	51,82	0,52	1	1
RES_Surgeons	50,92	0,51	1	1
RES_Emerg Doctors G_W	46,68	0,81	3	3
Ear specialist	45,78	0,46	1	1
Opthalmologist	41,29	0,41	1	1
RES_Emerg Doctors R_Y	38,00	0,76	3	3
Heart specialist	23,02	0,23	1	1
Anaesthetist	4,87	0,49	1	1
RES_Hospital Specialists	3,40	0,81	6	24

Table 2. Performance measures of resources utilization

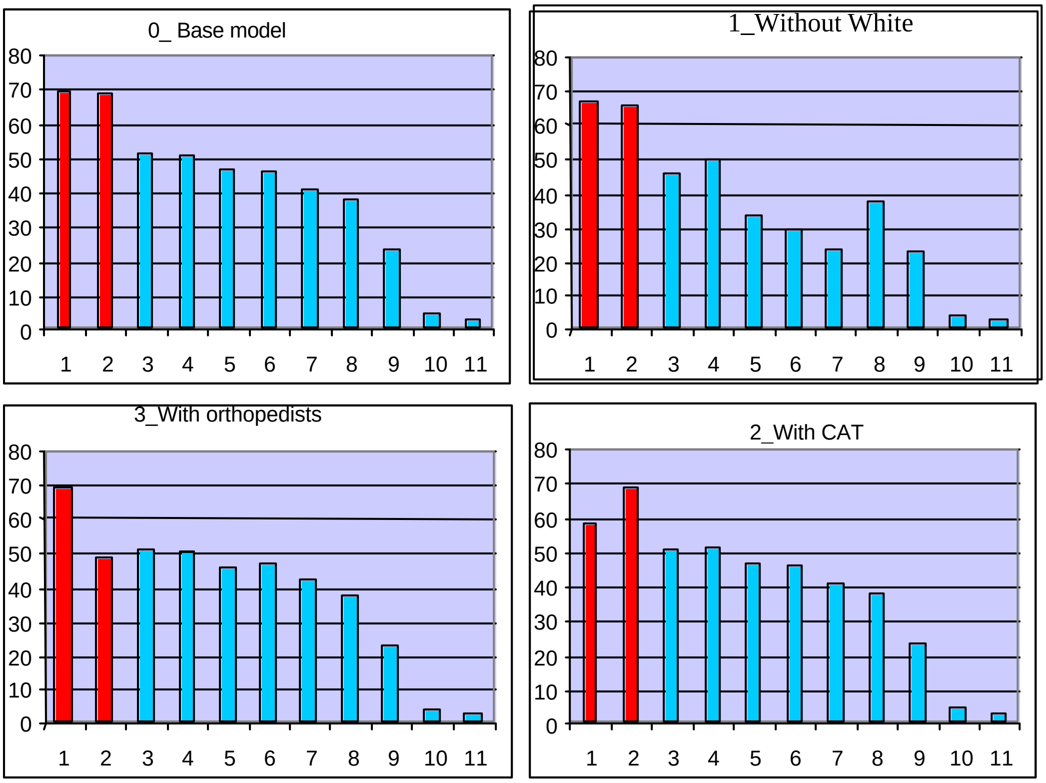
Table 3 presents the results relative to the queues for the different activities, showing critical situations in the waiting time for the first orthopaedic examination of patients with Green or White code, for the CAT and for the X-ray.

	Average Queuing Time	Maximum Queuing Time	Average Queue Size	Maximum Queue Size
Queue for 1st exam Orthop box	**138,62**	240,00	4,78	21,71
Queue for CAT	**92,74**	180,00	3,35	16,80
Queue for Orthopaedist	**22,43**	180,00	0,77	9,21
Queue for X-ray	**16,11**	180,00	2,97	25,01
Queue for Ear specialist	11,74	174,57	0,33	7,18
Queue for Ophthalmologist	9,22	152,07	0,23	6,02
Queue for Surgery box	7,62	189,89	0,24	9,34
Queue for Surgeon	7,13	131,69	0,12	4,47
Queue for Scan	5,48	160,29	0,16	5,58
Queue for Heart specialist	4,13	95,42	0,06	3,89
Reception Queue	3,03	36,26	0,37	10,14
Queue for 2nd Exam Surgery Box	3,00	120,12	0,09	6,83
Queue for 2nd Exam R	1,55	20,98	0,00	1,06
Triage Queue	0,93	72,46	0,15	7,33
Queue for 2nd Exam Orthop Box	0,80	28,45	0,02	2,91
Queue for Anaesthetist	0,68	21,16	0,00	1,29
Queue for Internist	0,49	8,95	0,00	1,03
Queue for 1st Exam Med box	0,49	59,90	0,03	5,85
Queue for Hospital specialists	0,28	52,64	0,01	4,11
Queue for 2nd Exam Med Box	0,02	8,41	0,00	2,23
Queue for 2nd Exam Y	0,00	2,46	0,00	1,11
Queue for Exsternal Exams	0,00	0,00	0,00	1,00

Table 3. Performance measures of queues

These observations have led to the formulation, simulation and analysis of alternative scenarios: in the first one, patients with a White code – characterized by long waiting time and high X-ray demand - were ignored, since they do not really need emergency attendance and might be diverted to other services; in the second one, a CAT and a radiologist in the CAT service were added; in the third one, an orthopaedist was added together with an additional examination box.

Figure 7 shows the percentage of the utilization time in the original and in the three new scenarios. In the first scenario it decreases slightly for all the resources. In the second one there is a decrease in the percentage of the utilization of the radiologist working for the CAT, and in the third one there is an even greater decrease in the orthopaedist utilization, that gets close to the value of the other resources.



1=RES_Radiologists TAC_Scan, 2=RES_Orthopaedics, 3=RES_Radiologists RX, 4=RES_Surgeons, 5=RES_Emerg Doctors G_W, 6=Ear specialist, 7=Opthalmologist, 8=RES_Emerg Doctors R_Y, 9=Heart specialist, 10=Anaesthetist, 11=RES_Hospital Specialists

Figure 7. Comparison of the percentage of the resources utilization time.

Figure 8 shows the simulation outputs concerning the four most critical queues in the original and in the three new scenarios. In the first scenario, there is a slight decrease of the average waiting time in all the queues. In the second one, things improve only for the CAT queue. In the third one, there is a great reduction of the waiting time for the first orthopaedic examination for Green or White code patients. Here the reduction is from 138 minutes to 19 minutes, while the waiting time in all the other queues does not change.

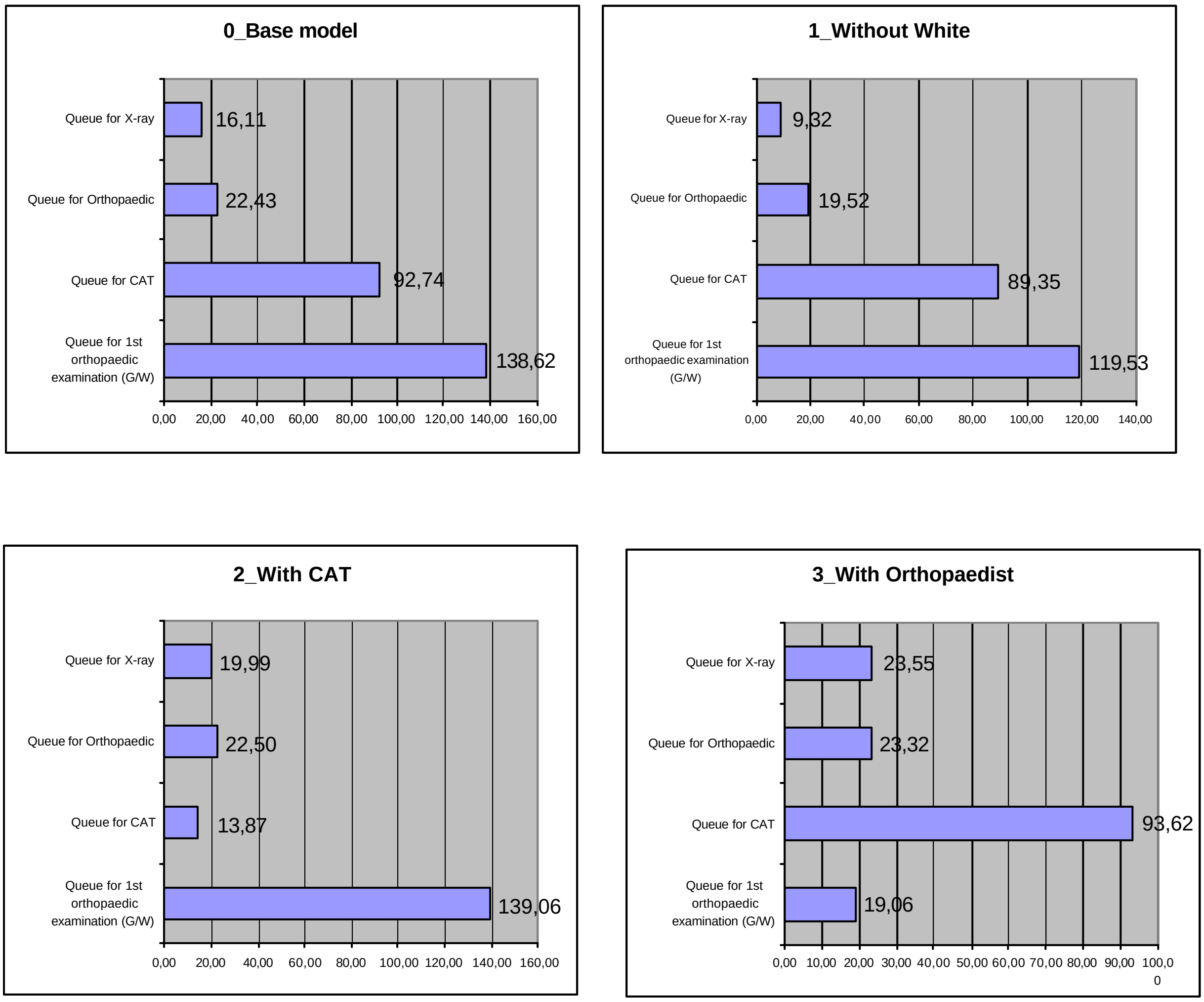


Figure 8. Comparison of the average waiting times (in minutes).

7. Conclusions

This work enabled us to build a simulation model that describes the standard work processes of a complex system such as one of the biggest AEDs in Rome. An accurate analysis of the AED processes has given the possibility to understand the system as a whole and to build a logical-mathematical-statistical model able to represent its objects, their attributes and their functional relationships.

This model has been implemented using the software *Simul8* and the simulation results have allowed us to identify the critical points of the organization of the AED, the long waiting times in some queues and the overloading of some resources.

It has been possible to formulate and evaluate alternative scenarios by changing parameter values, thus improving the performance of the system.

We like to point out that the benefits produced by the alternative scenarios have been greatly appreciated by the DEA manager who was already feeling the need for changes and was seeking quantitative support to reach a decision.

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