ANALYSIS OF A DIAGNOSTIC RADIOLOGY DEPARTMENT WITH DIFFERENT PATIENT FLOWS USING DIFFERENT DATA SOURCES

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ABSTRACT
In this paper, the authors propose a discrete event simulation model of a Diagnostic Radiology Department (DRD) within a public hospital, located in Italy. For quantifying examination process times, the model uses field data based on observations and data drawn from an official national document prepared cooperatively by various Italian radiology associations. These last data have been adapted to the specific case study after an extensive data collection campaign.
In order to validate the model, patient record data drawn from the department information system have been exploited. Despite the carried out "scenario analysis" results are strictly related to the investigated case, the model and the method for implementing process time data in a similar case could be generalized, provided that sufficient field data are available.

Keywords: simulation, health care, radiology department

1. INTRODUCTION

Health care efficiency in developed countries' societies has always deserved a great attention by the governmental authorities because of the huge amount of public expenditure in this sector. Concerns are amplified also for the generalized population ageing, which determines a growing demand of services. The increasing health care cost trend in most industrialized countries and, in particular, in the 34 members of the OECD is confirmed, for example, in (OECD 2011). It highlights an increasing average percentage of the GDP directed to this sector, from 4% to nearly 10% over the past fifty years. More worrying, this percentage is growing considerably faster than the GDP increment itself. The public sector is the main source of health financing in all OECD countries (except for Chile, Mexico, and the United States) with an average share (in 2009) of 72%, that has remained relatively stable over the past 20 years. As pointed out in the report, "while there is some relationship between higher health spending per-capita and higher life expectancy, the relationship tends to be less pronounced as countries spend more on health". Therefore, beyond a certain level, different indicators, related to the quality of services (which is reflected in the quality of life of an ageing population), have to be adopted to ensure that the additional money spent brings about measurable benefits. As stated in the report, "in a context of population ageing, it will also become increasingly important to monitor the financing, delivery and quality of long-term care services across OECD countries."

Confirming this outline, for example, population percentage over 65 years has doubled from around 10% in 1960 to around 20% in 2009 in Italy and Germany, which are the countries, among OECD members, that report the bigger figures, just after Japan (22.7%). The need of a strict cost accounting system, along with the constraint of maintaining acceptable service quality levels, has led to the implementation of Operations Management (OM) techniques in Health Care Systems (HCSs).

Hence, many health care researchers and managers have turned to OM literature, consolidated in the industrial and service sectors, when seeking answers to the many problems faced in delivering health-care services. In this context, computer simulation is a valuable tool for HC decision-makers for achieving their goals, enabling experimentation of several solutions (e.g. extra resources, different facility layouts, alternative resource planning) at relatively low cost. An overview on this subject can be found in (Jacobson et al. 2006), in which also the various areas of application are outlined. Hospital departments are characterized by high investments in medical equipments, of which high utilization and availability are essential for meeting health-care and economic goals as well. Complexity in sizing department capacity and management of equipment and human resources relies on meeting the service demand represented by patient flows of different origins; furthermore, priority rules in dispatching these flows are often implemented to manage limited resources. The Diagnostic Radiology Department (DRD) in a hospital is a significant reference case, characterized by high investment in equipments that are shared by different patient pathways. For this reason, a DRD often represents the bottleneck in a hospital system. Moreover, it is characterized by an inherent complexity: first, because its performances depend on the interaction of different resources (machines, physicians and technologists); secondly, because it also shows strong inter-dependencies with the Emergency Department (ED) of the hospital, as observed, for example, in (Johnston et al. 2009). In such situations, in general, it is worth modelling the processes carried out in hospital departments, identifying the elements involved and, in order to appreciate quantitatively technical, economic and service quality performances, stochastic computer simulation models prove to be very effective. However, these models require a large amount of data, which are rarely directly available from hospital information systems. These systems are often built solely on clinical needs and unable to track the various process steps (Fryk and Steins 2010).

In the present paper, the authors propose a discrete event simulation (DES) model of a DRD within a primary importance public hospital, located in Southern Italy. The model is based on a process algebra language, called chi (Hofkamp et al. 2008). Chi has been used for modelling, simulation and control of manufacturing and warehousing systems, e.g. in (Andriansyah et al. 2011) and for HCS as well. For quantifying examination process times, the model uses data from the department information system, field data based on observations, and data drawn from an official national document edited on the behalf of various Italian radiology associations (VV.AA. 2006).

The paper is articulated as follows: in Section 2 a brief literature survey addressing specific issues (radiology department simulation models and the quality of available data) is given; in Sections 3 and 4 the case study, along with the available data from the DRD information system, is illustrated; in Sections 5 and 6, the employed method for collecting on-site data of process times and for the joint use of national official data is given; in Sections 7, 8 and 9 the DES model of the system is illustrated and the results for the current equipment configuration and for an enhanced equipment configuration are commented and compared; finally, in Section 10 some conclusive remarks are reported.

2. LITERATURE SURVEY

Issues related to “scenario” analysis, exploiting and adapting available data drawn from hospital information systems, and modelling of radiology departments are summarized.

In (Centeno et al. 2000) the authors analyse the radiology department at Jackson Memorial Hospital (Miami, USA) by means of a DES model. The aim of the study is comparing six scenarios, including the existing one, in terms of utilization of human resources and operating rooms, of waiting time for patients and of costs (salaries for nurses and technologists and equipment costs, calculated per operation). In particular, the authors highlight the problem of the quality of data drawn from the hospital database. Filtering out incoherent records, they determine the parameters for several probabilistic distribution functions used in the model. The analysed scenarios consider both organizational variations (the number of technologists per operation and a one working day extension) and physical improvements (e.g., an additional operating room and a pre-holding area for patients).

In (Swisher et al. 2001), the authors present a DES model of a physician clinic environment. They highlight the advantage of the use of an object-oriented paradigm approach for re-use and easy extensibility of the model. They also present an animated visual representation of the entire system to permit easily interaction and understanding by the personnel involved. The model is organized in a hierarchical manner with the top level including a centralized information centre for receiving calls and scheduling appointments and one or several identically instantiated objects representing a multiple network of family practice clinics. Actually, the paper is focused on the description of the model of one clinic only. After the description of the process steps and of the model components, the authors remark the difficulty arising from the procurement of statistically reliable data, regarding the probability of the various steps to take place and of process time distributions. The main complication is represented by the differences stemming from ten different categories of patients, classified according to their health conditions. Therefore, instead of affording a very cost and time-consuming task, their solution is adopting a triangular distribution for each process, estimated by medical experts. A fractional factorial design is then adopted in order to determine the input factors (staff sizing and rooms), which significantly affect a global performance indicator called “clinic effectiveness”. This is defined as a scalar measure, comprising, in a weighted fashion (depending on the clinic owner or administrator's viewpoint), both profit and patient service levels (e.g., waiting time).

In (Johnston et al. 2009) it is highlighted the problem of ED access block in Australian hospitals, in particular ascribable to an excessive workload of the DRD, since the strict interconnection between the two departments. Their analysis is limited to the ultra-sound examination process only, of which the various steps are depicted, prior to the set up of the DES model itself; this is built with commercial software, typically used in the industrial context. Three types of patients are also generated, according to the possible admission of in-patients, out-patients and emergency patients. For process time characterization the authors identify the most requested types of examinations (accounting for 86% of the total) and then adopt gamma distributions. The results of the simulation describe the current situation only and some recommendations are drawn. Also in this paper some remarks are pointed out about the quality of the available data, considered of crucial importance and about the need of filtering out a large amount of erroneous records.

Fryk and Steins (2010) investigate in their paper how an appropriate IT (Information Technology)/IS (Information System) infrastructure within a hospital could support a process oriented approach, which represents the primary step for applying more sophisticated analysis tools, such as DES. The construction of any model consists of two fundamental activities: structural modelling (identifying process steps and needed resources) and data collection and parametrization (e.g. arrival patterns, activity durations and resource availability). The latter can be notoriously very time-consuming and can be much more eased if the necessary information is already available in existing ISs. This is routine and widespread in the manufacturing sector, but is problematic in HCSs because of the quality of data, rarely organized in a "process-oriented" manner, reporting all the relevant time-stamps of the process (e.g. patient tracking through various steps) and based, instead, on clinical functionality. In their case study at Danderyd University Hospital (DUH) in Sweden, it is highlighted the strong interdependency between the Emergency and the Radiology Departments and a process mapping, from patient admittance to his discharge, is carried out. The authors point out the interfacing problems arising from the use of two different ISs at the departments and that, furthermore, many data about quantitative process control are absent (for almost half of the time-stamps) or only partially available, due to the lack of clear activity start definitions. Therefore, their conclusion is that for obtaining a reliable DES model aimed at finding where bottlenecks origin (being flow-time reduction their goal to meet service quality obligations) many data have to be acquired by means of on-site observations and/or expert estimations, even though subjectivity may be introduced.

In the present paper, the analysed process is very similar to that described by Fryk and Steins (2010) and the utilized data come from the integration of national official data and on-site observations for process time quantification, together with the radiology IS data for validation purposes.

3. CASE STUDY

3.1. System description

The analysed DRD is a complex diagnostic unit, able to perform several kind of examinations, located in the hospital "Madonna delle Grazie" in Matera (Italy), which is the second hospitalization pole of Basilicata Region. The department offers diagnostic services for in-patients, ED-patients and out-patients. It consists of machines and human resources with different specializations: radiological technologists to operate the machines, physicians for reporting the results of the examinations, attendants to help moving patients, nurses for preparing them for some particular examinations and administrative staff in the reception. The equipment consists of X-ray machines, ultrasound scanners and one working Computed Tomography (CT) scanner. The ultrasound examinations have been excluded from the present analysis, because the involved process can be considered as a stand-alone process, requiring one physician only, who leads the examination and is enabled to print the resulting images and report immediately. As depicted in the layout scheme in Figure 1, all the machines (except one), are located in separate rooms.

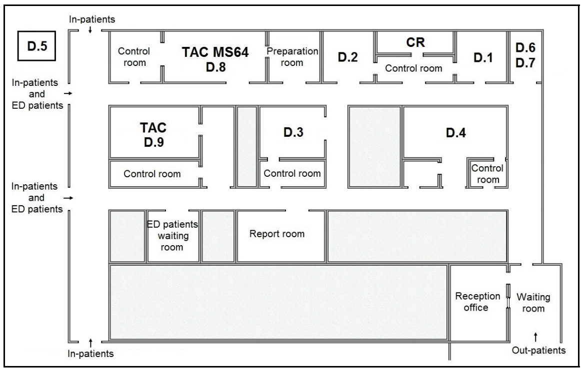

Figure 1: Radiology Department Layout

The group of X-ray machines comprises seven units; of which those numbered from 1 to 5 are general purpose machines, whereas machines 6 and 7 are special purpose, respectively for mouth/cranial examinations (OPT) and for densitometry examinations (BDS - Bones Density Scanner). These last machines are located in the same room and therefore are unable to work simultaneously for safety and practical reasons. Constructively, machines 3 and 5 are identical and constituted by an irradiating tube (the last machine is dedicated to ED patients and is located outside the department area, closer to the ED); for this reason they are quite flexible and versatile in executing various types of examinations. Machines 1, 2 and 4 are equipped with a radiological table and contrast medium examinations can be performed exclusively on machine 1. Machines (except for 4, 6 and 7) are based on "traditional" X-ray technology. To complete the process, it is necessary to read-out the latent images on the plates, by means of an additional machine denoted as "Computed Radiography scanner (CR)", which also enables digitizing and storing them electronically in the department image DB. On the contrary, among the general-purpose machines, machine 4 is the only "Direct Radiography (DR)" machine, making the examination process fully digital and resulting as the most accurate and fast machine. For this reason, although any kind of examination, except for contrast medium examinations, could be performed on any of the general-purpose X-rays machines, technologists show a clear preference for machine 4. Moreover, although machines 1 and 2 are constructively similar, there is also a slight preference for the first over the second, because its control system is newer and simpler. All the above-mentioned characteristics have been included in the model. As regards the ED dedicated machine (D.5), its utilization is indeed very marginal, because it is considered inadequate by the staff, both under the technical aspect (poor image quality) and the logistical aspect (examination room too tight for moving and transferring patients, mostly on litters). The

CT machines present in the department, according to Figure 1, have been numbered as 8 and 9. Currently, the only working machine is D.8, because machine D.9 is in a failure state and the hospital management has decided not to repair it because of the expensiveness of replacement parts and of its obsolescence. Machine D.8 is instead a last generation piece of equipment, which can perform multi-slice high resolution scans.

About the department human resources, attendants for moving and accommodating non-autonomous patients have been excluded from the analysis (indeed, technologists can also perform this function). In general, technologists represent in this system a shared resource during the examination phase to operate the X-ray machines, whereas physicians represent a shared resource during the reporting phase. The CT scanner requires both the roles (i.e. dedicated physician and technologist) because, in most cases, their job activities are strictly complementary in the course of the examination itself. The analysis and simulation model is focused on the examination phase only, which ends storing the resulting digital images in department image DB, for successive retrieving and reporting. The technologists are modelled as interchangeable among the X-ray machines (except for the CT scanner with a dedicated one) and requested by the machines when needed.

3.2. Process work-flow and patient flow

The diagnostic and examination process can be summarized in five principal stages: (1) examination request generation, (2) patient reception and registration, (3) examination execution, (4) reporting and (5) report delivery. Based upon the different origin of the requests, the whole examination demand can be categorized into four different flows: a) in-patients and b) urgent in-patients (whose examination requests are generated by doctors in the various hospital departments); c) out-patients (planned component of the demand, whose requests are generated by family doctors and are scheduled on an appointment base) and d) ED patients. For out-patients, the number of requests to work out daily in the DRD comes from a fixed weekly schedule, detailed for each day of the week with a planned number of certain types of examinations.

The reception opening time for out-patients consists of two 6-hour work-shifts (from 8 a.m. to 2 p.m and from 2 p.m. to 8 p.m., with different technologist availability) from Monday to Friday and one morning shift on Saturdays. Newer requests are queued in the booking system externally by the "CUP" office (Centro Unico Prenotazione - Unified Booking Centre) and the relative waiting time, measured from the booking moment to the appointment day, can vary from days to months (especially for CT examinations), depending on the examination type. This "long" waiting period has been excluded from the present analysis, which is focused on the simulation of the DRD only, that's to say from the moment the patients arrive on. Patients of types a) and c) are processed only during the reception opening hours, whereas patients b) and d) need a service response at any time (0-24h). When coexisting, the priority order is set, in descending importance, as: b) and d), considered equal, c) and, finally, a). In this regard, one of the major concerns of the DRD process management is arranging the external planned demand and the random component, represented by the emergency/urgent demand. Reception staff has the duty of registering patient arrivals in the department IS and pre-allocating rooms on the basis of examination types. The list of waiting patients builds up the work-list for the technologists, visible on every computer terminal, in each room. In addition, patient types are identifiable by means of different tags, for prioritization purposes.

In the present analysis, a fundamental time-stamp in patient tracking for successive model validation (based on waiting time computation) is the time of arrival of a patient as recorded in the department IS. It is represented by the time-instant when reception personnel decide to register a patient arrival at the department. For patients a), registration "should" happen as soon as a patient arrives at the DRD, after that the receptionist, received an internal request (in paper form), decides his transfer from the relative hospital department. As explained successively, this is not always the case (therefore registration can take place previously than the effective arrival). For patients c), the time of arrival is represented by the patient show up on appointment. For patients b) and d), the examination requests are generally sent in electronic form and the patients are immediately transferred to the DRD. Due to the use of different ISs (at the moment of the present analysis), manual data transcription and input are required, but they are generally carried out immediately because of the high priority and can be considered accounting for patient transfer time. When the reception is closed, the technologists themselves execute the registering activity. Once registered, patients wait in dedicated spaces for an inter-phone call for going autonomously, following signposts, to the examination room (this generally happens for out-patients) or are accompanied by attendants or by technologists themselves (this happens for in-patients and ED patients, who are generally on wheelchairs or wheel-beds).

4. DATA AND MODEL ASSUMPTIONS

The available data, queried from the Radiology Information System (RIS), consist of a table-sheet (in the following, referenced to as "DRD-data"), reporting the number of all the different examinations (classified on the basis of the examined body-part and technique), with denominations and codes, performed in the department in the course of a time period, detailed with the used diagnostic machine and the type of patient. In the real system, a single patient can undergo a series of examinations (i.e. various body segments). This information is lost in the above data, which are in aggregated form, reporting for each machine, the resulting sum of every performed examination. Since

DRD-data are used to derive the inter-arrival times of the served entities, in the simulation model the examination request generation processes are realized by means of four “examination-generators” (representing the four different flows of patients), which are not properly “patient generators”. Each request consists of one type of examination only. The examination requests are treated as moving objects in the model, representing the “patients”, as if, in the real system, for each patient, there were one examination only to perform.

Indeed, DRD data have been marginally arranged to take into account that some types of examinations (i.e. body segments, which in DRD-data appear as separate counts) can be aggregated into typically executed sequences. In particular, for CT examinations some typical sequences have been found, on the basis of the available collected process time data and of what most likely happens. For example, since upper-abdomen and lower-abdomen CT scans with and without contrast medium are very rarely executed separately, they have been aggregated into one examination, for which more observations are available. Other aggregated figures have been adopted for the sequences brain-chest-abdomen and chest-abdomen (both with and without contrast medium), assumed on the basis of the found distribution percentages of these types of examinations. This latter information has been derived from a detailed analysis of CT data records referring to three months.

As regards X-ray examinations, the only possible aggregation could be employed for femoral and lumbar bones density scans, executed only on machine D.7, which are very rarely executed separately. Since the present analysis is carried out with regard to steady-state conditions, generators are modelled as time-random Poisson processes.

Table 1: Inter-Arrival Times derived from RIS Data

	In-patients (G_0)	Urgent in-patients (G_1)	Out-patients (G_2)	ED-patients (G_3)
Total number of examinations (aggregated)	13,543	654	18,375	15,984
Reference hours	2,550 (reduced reception time)	8,760 (1 year)	3,366 (reception time)	8,760 (1 year)
Average inter-arrival time [min/pat]	11.30	803.67	10.99	32.88
Patient mix in the model time-span	41.92%	0.59%	43.09%	14.40%

An assumption in the model is that the simulated time is limited to reception working time. In this way, on the one hand, it is possible to simulate the system without the need of complex routines for time checking and system configuration variation (due to the technologist staff sizing change during the shifts and to the restricted accessibility for some types of patients). In this way, it is possible to analyse the system under the most demanding conditions, subjected to the four co-existing patient flows. In order to derive the average inter-arrival time intervals for each type of patients, their total numbers in one year and the corresponding reception available working hours or total yearly hours have been used. Data of 2010 have been considered as a reference; according to the hospital personnel's experience, data do not vary significantly in the short-medium term. For in-patients, the available hours have been reduced, because during some daily periods it's not possible to ask for their transfer (to avoid overlapping with some routine activities, as the daily medical check or dining time).
Table 1 reports figures and calculations.

5. PROCESS TIMES AND DISTRIBUTIONS

Since it's impractical (or even infeasible) to collect statistically reliable data for the very numerous types of all the possible examinations on each machine, data collection work has been limited to the most requested examinations, in an observation period of several days during different weeks. Consequently, in the simulation model, some assumptions have been made about the duration of examinations with no available data. For the latter, a combined approach has been implemented, employing on-site collected data and data drawn from a national official document, edited on behalf of various Italian radiology associations (VV.AA. 2006). It lays down a national codification system for examinations, and reports for each examination mean process time needed for execution and reporting, taking into account also auxiliary activities needed by law (information, personal approval, medical justification verification).

The published mean values are derived from findings in 15 hospital departments. A great limitation of the information is the lack of process variability. An extensive data collection campaign has been carried out, in order to adapt the reference data to a specific case. A minor observation is that, preliminarily, examination code conversion of DRD-data has been necessary, because the hospital department used a different codification. On-site data collection methods of examination times and their exploitation in the model slightly differ according to the kind of examination.

For CT examinations, collected data quantify machine room occupation time. In some cases (contrast medium examinations for out-patients) there is the need of a pre-processing treatment carried out in a contiguous room, but this doesn't affect the duration of the successive examination. For eight different types of examinations it has been possible to collect a discrete number of observations, whereas for other examinations their number was too limited to make a significant sample (only data on patient waiting times have been used successively from these recordings). Data elaboration results (reporting Italian examination codes) are shown in Table 2, along with maximum likelihood estimated parameters for gamma probability distributions and results of goodness-of-fit tests at the significance level 0.05. These gamma PDFs are used in the simulation model. The *k factor* represents the ratio between the mean value from the observations and the average duration of the corresponding code reported in (VV.AA. 2006). The two codes denoted as fictitious consist of sequential scans on body segments, which don't exist as unique examinations in the document. For them, a reference average duration (with a presumptive calculation of *k*) has been assumed as the sum of the time for the first scan and half the time of the subsequent scan(s). As reported in the table, for three codes, tests have failed (it has been verified also that other possible PDFs don't fit satisfactorily); for them, empirical distributions are then used. For all other CT examination codes not comprised in the table, the combined approach implemented in the model consists of: 1) assuming as mean value μ half the average value drawn from the document (assumed *k ratio* equal to 0.5) and 2) assuming a gamma PDF for the process, with the minimum found shape parameter $\alpha=3.3$ and scale parameter β, calculated as μ/α. Doing so, a conservative behaviour of the model results, both for process durations and for variability (adopting the maximum found coefficient of variation $c=\sigma/\mu=\sqrt{(1/\alpha)}=0.55$).

Table 2: CT Examination Data

Examination Code	Sample size	μ (min)	σ (min)	k	MLE (γ)		Goodness of fit tests [2]		
					α	β	KS	CM	AD
3.F.1.1	69	9.65	5.83	0.51	3.30	2.92	Not r.	r.	r.
3.C.2.6	38	20.53	8.91	0.55	4.81	4.27	Not r.	Not r.	Not r.
3.B.5.1	37	6.86	2.02	0.36	-	-	**r.**	**r.**	**r.**
3.B.4.2 3.F.1.2	18[1] (8+10)	13.67	3.76	0.51	-	-	**Not calc.**	**r.**	**r.**
Fictitious code 1	13	22.04	6.02	0.37	15.99	1.38	**Not calc.**	Not r.	Not r.
Fictitious code 2	11	19.96	7.07	0.44	8.25	2.42	**Not calc.**	Not r.	Not r.
3.B.4.1	8	8.63	3.54	0.45	5.83	1.48	**Not calc.**	Not r.	Not r.

[1] Resulting aggregated number of two different examination with the same duration according to (VV.AA. 2006)
[2] KS: Kolmogorov-Smirnov - CM: Cramer-Von Mises - AD: Anderson-Darling (r.: rejected - not calc.: not calculated)

A similar approach has been used for X-ray machines. From the collected available data, derived in the way explained in the next section, it has been possible to include several different examinations into a unique group, being characterized, according to (VV.AA. 2006), by the same duration. Results of statistical elaborations are summarized in Table 3.

For all the other possible examinations, not belonging to the reference group, in the simulation model, at first, it is assumed the *k ratio* to be characteristic of the particular used machine. In this way, average durations μ can be calculated from the corresponding values reported in (VV.AA. 2006). Then, gamma PDFs are employed, assuming a constant shape parameter α, characteristic for each machine (as reported in Table 3) and variable scale parameters β calculated as μ/α. Machine D.5 isn't reported, assumed to be no longer in use. For machine D.6 no observations are available; as it adopts direct radiography technology, the parameters of D.4 are utilized.

Table 3: Data for X-ray Machines

Machine	Sample size	Number of performed examinations in the same process			Reference examination time (min)	k	MLE (γ)		Goodness of fit tests		
		1	2	3			α	β	KS	CM	AD
D.1-D.2	61	32	10	3	7	1.67	6.03	1.94	Not r.	Not r.	Not r.
D.3	38	32	3	-	7	1.45	6.98	1.46	Not r.	**r.**	**r.**
D.4	66	50	5	2	7	0.81	3.96	1.43	Not r.	Not r.	Not r.
D.7	21	21	-	-	12 (*)	1.08	13.38	0.97	**Not calc.**	Not r.	**r.**

(*) Presumptive duration calculated as the sum of the durations of femoral and lumbar bones density scans

6. DATA COLLECTION OF X-RAY MACHINES

As previously stated, generators in the model associate to each patient a request for one kind of examination only, whereas it can happen that a patient undergoes a series of different examinations on the same machine. In order to derive exploitable data also from the observations of these cases, albeit representing a minority (as reported in Table 3), a segmentation of the entire process has been employed, according to the criterion illustrated in the example in Figure 2, depicting a process with three different examinations. In the simplest case of a single examination only, room occupation time by any patient has been assumed to be the process time used for statistics. Therefore this duration, besides the characteristics of the used machine and the examination technique, is also strongly affected by the patient conditions (i.e. his moving capabilities and age). These latter characteristics are not explicitly included in the model, but are included, indirectly, in process time PDFs.

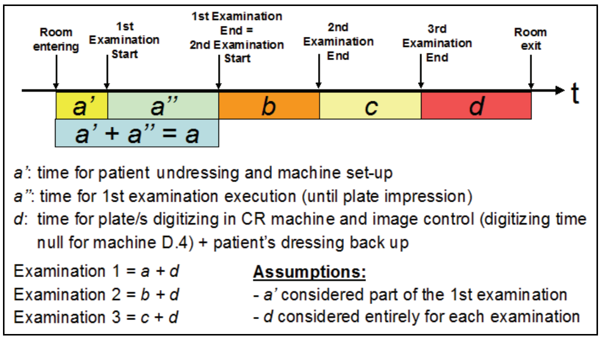

Figure 2: Time Segmentation Example

Some remarks have to be spent about the activities carried out by technologists. It's necessary to take into account that they can be busy in a series of auxiliary activities not directly related to performing examinations (i.e. calling patients, helping in moving non-autonomous patients to the examination rooms, talking with doctors, physiological pauses). Therefore, a machine/room can be free for receiving a patient, whilst a technologist can be not ready yet. The time spent in these “extra-activities” by a technologist, working on the assigned machine, can be defined and measured as the time span between the time instant a room/machine gets free and the entering time of the next patient, under the condition that this patient is present. If a patient were not present, whatever a technologist is doing wouldn't have any influence, as shown in Figure 3.

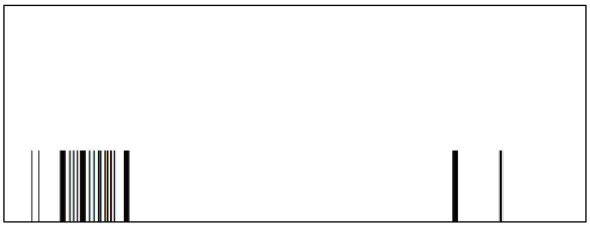

Figure 3: Technologists’ “Extra-Time”

Measurements carried out in the course of the on-site surveys (87 data in total), quantifies the average time spent in “extra-activities” as about 3 minutes. For the sake of simplicity and effectiveness in modelling, no variability for this “extra-time” has been assumed. The number of technologists has been considered constant during the entire simulation time span. This number comes from the average value of a typical monthly personnel roster (4.8 per shift), rounded to the nearest integer (5). One of these technologists is always assigned to the CT machine, whereas the other ones are shared among the X-ray machines.

7. SIMULATION MODEL DESCRIPTION

The DRD has been analysed by means of a DES model written in chi. The focus is on the examination process, from the moment a patient has entered the department until the examination has been executed and the patient can exit the system, in steady-state conditions. The model includes the characteristics of the real system: the diverse priority assigned to patients; the preferential use of machines; the use of a shared resource, represented by technologists; the inability of two X-ray machines, in the same room, to operate simultaneously; the variability of process times; “extra-activities” carried out by technologists.

The capability for each machine of executing an examination code is derived from DRD-data. In this way, no specific knowledge about the examination technique and the technical equipment are required. In addition, each generator has to reproduce statistically the requested types of examinations, as drawn from DRD-data. Therefore, by means of an automated routine, which can be applied whenever similar data are available, data are first divided according to the types of patients, then sorted by the kind of examination and frequencies and cumulative frequencies are calculated. Successively, the generators in the model adopt an empirical distribution approach to convert a random draw in the interval [0,1) into an examination code.

In Figure 4, the logical dependencies among the exploited sources of data and the model components are illustrated graphically.

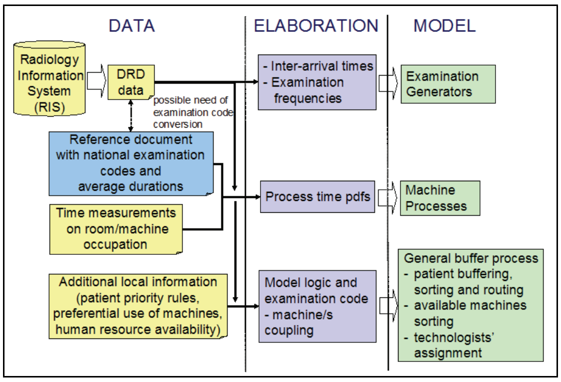

Figure 4: Different Data Sources

The resulting model of the department, reported in Figure 5, consists of the following processes:

- four generators G_i with exponentially distributed inter-arrival times (corresponding to the different flows of patients) and reproducing, statistically, the examination requests;
- general buffer process *BP*;
- eight machine processes XD_j, implementing gamma PDFs for process times, as explained in Section 5 (process XD_4 is indeed not utilized, because representing the ED dedicated machine);
- fixed delay process *T*, for modelling technologists' “extra-time”;
- exit process *E*, recording simulation output.

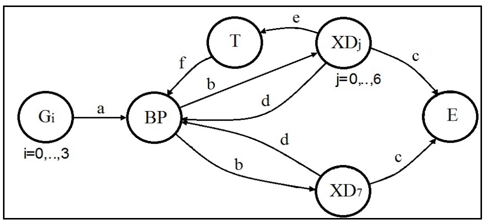

Figure 5: Model and Processes

Generators send patients, through channel *a*, to general buffer *BP*, in which a sorting process, depending on the priority rules adopted for patients, is executed. The “patient” data-type contains both the necessary information for the logical execution of the simulation algorithm and for later simulation-output elaboration. The first set of data comprises: a priority integer number; the requested examination code; a set of natural numbers (machine-examination coupling), representing the numbered machines able to perform the examination code. The second set of data consists of the entry times in buffer *BP*, in the room/machine process, and the exit time from the system, together with the origin of the patient and the utilized machine. From buffer *BP*, the patients are sent, through channels *b*, to one of the machines XD_j, able to perform the requested examination, under the conditions that 1) the machine isn't busy and 2) one of the technologists is available (this condition is skipped for XD_7, representing the CT machine with a dedicated technologist). If this is not possible, the patient has to wait in the buffer. Also the condition of one examination at a time executable by process XD_5 or XD_6 (representing the special purpose machines D.6 and D.7 located in the same room) is taken into account in process *BP*. In order to consider the preferential use of machines, the list of ready machines is sorted according to an integer number ranking. Technologists are modelled as a resource, shared among the different machines, except for process XD_7. At the end of each examination on any of the processes XD_j, the patients are sent, through channel *c*, to exit process *E*. A data-type containing the number of the not-busy machine and its associated preferential-use integer ranking number is sent, through channel *d*, to buffer *BP*, where the list of available machines is sorted according to their preferential use. At the same time, for all the processes, except for XD_7, a "signal", representing the leaving technologist, is sent, through channel *e*, to process *T*, where his availability for the next examination is delayed by a fixed amount of time representing his engagement in "extra-activities". Then, process *T* releases each technologist, through channel *f*, to buffer *BP*, which collects them and, upon request, dispatches them back to the machines. The model doesn't take into account machine breaks and repairs because their effect is negligible (as verified in additional modelling, not reported). In the following, some simulation results with the current machine configuration will be illustrated, along with the analysis of results obtained with the introduction of an additional CT scanner.

8. RESULTS WITH THE CURRENT SYSTEM

Attention is focused on average waiting time of the different types of patients (assumed to be representative of the offered service quality level) and on utilization of machines and technologists. Simulation results come from 300,000 minutes runs, corresponding to 1.5 year continuous working time of the reception.

The first two sets of results have been obtained with the current equipment configuration (in which machine D.5 is no longer in use) varying the average number of available technologists, shared among the X-ray machines, from 4 to 3 and highlighting the effect of increasing the time spent in "extra" activities (the total number of working technologists has to be incremented by one unit, dedicated to the CT scanner).

In the following figures, along with the simulation results, the observed average waiting-time values in the real system, obtained from additional information (drawn from the RIS), are also reported. In particular, the observed waiting time for each patient has been calculated as the difference between the registered check-in time at the reception and the room entering time, collected with the observations.

In Figures 6 and 7, waiting-times in X-ray examinations for the different types of patients, respectively with 4 and 3 available technologists, can be compared.

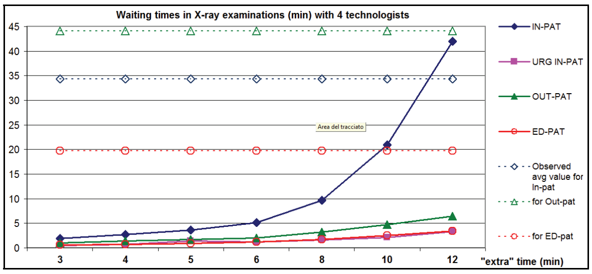

Figure 6: Waiting Times with 4 Technologists

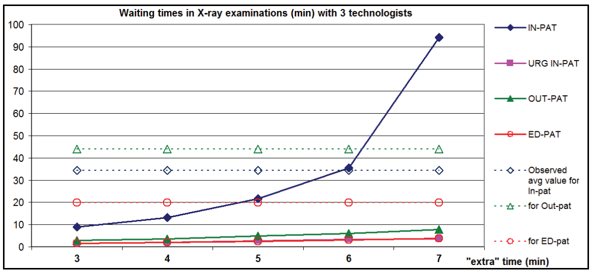

Figure 7: Waiting Times with 3 Technologists

For each case, the results show the intended behaviour of the model as regards the process priorities assigned to patients. A disagreement is noticeable with the observed values, which are greater then the simulation results. The following observations can be made.

a) The out-patient arrival process is different from a time-homogeneous process, being not time-randomly distributed but scheduled: for this reason, it can't be used for validation purposes of this specific model; furthermore, observed waiting times are intrinsically high, because of the generalized tendency of many out-patients of showing-off largely in advance with respect to the appointment time (due to public transport constraints).

b) In-patient data for X-ray examinations are biased by the circumstance that the registering activity expedited in the reception is largely anticipated and doesn't reflect the true arrival of a patient at the system; therefore, in-patients can be first registered and successively, when the system utilization conditions permit this, physically transferred.

c) ED patients are indeed subdivided into different priority levels and therefore the observed average value is affected by the presence of very low priority patients.

d) Results obtained from the model itself could be underestimated because of the real circumstance of performing several X-ray examinations on a single patient and of the lack of observations for some long duration examinations (performed with a contrast medium), for which, in the absence of data, only the illustrated combined data approach has been used.

In Figures 8 and 9, utilization of machines and of technologists are shown. Technologists' utilization is calculated as the ratio between the time-average number of not available technologists (indifferently engaged in performing examinations or in auxiliary activities) and their total number (3 or 4); their utilization in “extra” activities specifically highlights the engagement in this kind of activity. In both cases, results highlight that the most utilized resources are the CT scan (D.8) and the technologists, whose utilization linearly increases, varying the “extra” time, to the extent that a utilization value close to one makes the system unsteady (with ever increasing waiting time and queues for in-patients).

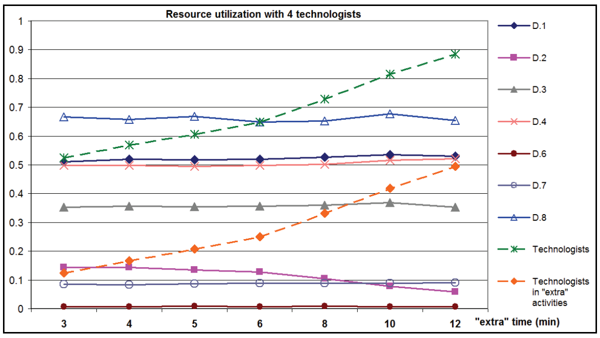

Figure 8: Resource Utilization with 4 Technologists

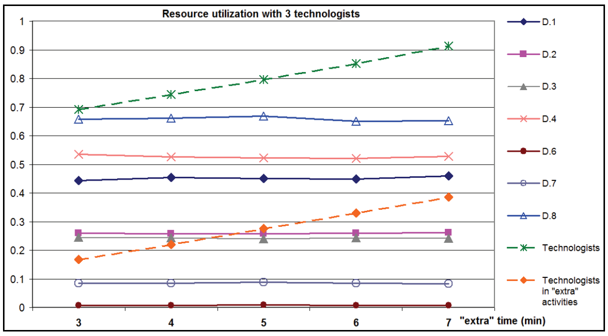

Figure 9: Resource Utilization with 3 Technologists

With four technologists, even doubling the time spent in “extra” activities, with respect to the observed average value of 3 minutes, the simulated model isn't stressed and their utilization doesn't exceed 0.6. With three technologists, doubling the “extra” time, their utilization, already quite high with the initial value (around 0.7), attains the value of 0.85.

In Figure 10, waiting-time results for CT examinations, both with 3 and 4 technologists, are reported. Since they aren't affected by the “extra” time variable because of the dedicated technologist on the machine, the different outcomes are due to the intrinsic variability of the model. Excluding the comparison with the observed values for out-patients for the same reason illustrated in point a), results show a good accordance with the observations. More specifically, the reported results show for in-patients (70 observation data) a maximum relative difference of around -25%, for ED patients (43 observations) a maximum relative difference of around -45% and for urgent in-patients relative differences in the range -25% ÷ +20% (but the number of observations is limited to 23). In the same figure, the 90% confidence intervals of the average observed values are reported.

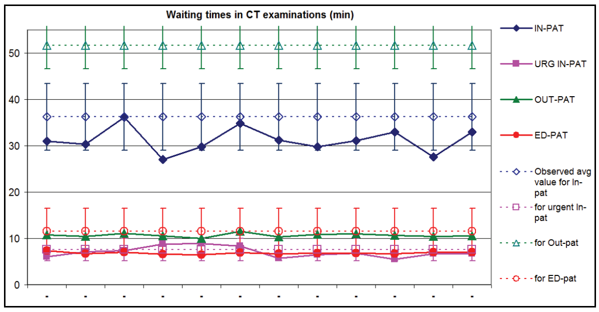

Figure 10: Waiting Times for CT Examinations

The good accordance is explainable, besides the greater accuracy in modelling CT examinations because of one scanner only, by the better quality of data for validation purposes. In fact, probably, in-patient check-ins are performed just when there is the real possibility of executing examinations, being the receptionists more aware of the job-order processing on one machine only. Therefore, the registered values can represent the “true” patient arrivals at the system. Additionally, ED patients for CT examinations are mainly in critical conditions, and therefore the observed values are not biased for the reason mentioned in point c). As the results for waiting time in X-ray examination show the possibility of reducing the number of shared technologists from 4 to 3 maintaining acceptable waiting time values, in the following section the impact of introducing an additional CT scanner is evaluated. This would require just a different assignment of the technologists, with a dedicated one for the scanner, but would also require an additional physician in its control room.

9. RESULTS WITH AN EXTRA CT SCANNER

In the following, the extra CT scanner will be denoted as “D.9”.

A first hypothesis to be evaluated consists of introducing a “minimal capability” CT scanner (possibly, a model cheaper than standard, but still with a good image quality), able to perform only specific types of examinations without the use of a contrast medium (as the cranial scan, for trauma cases). In particular, it should be able to process one or both of the two most requested examinations in the aggregated flows of patients (accounting for 18% and 8% respectively of the whole CT examinations during the reception working time, which are the cranial scan and the high resolution chest scan). Without the need of the use of a contrast medium, these types of examinations would not require an additional preparation room and nurse, but still an additional physician. A second hypothesis consists of an additional CT scanner, identical to the existing one, but, due to a management choice, with a limited utilization to examinations without contrast medium (w.o.c.m.) only, for space and human resource limitations.

The waiting-time results reported in Figure 11 show that the benefits of the first hypothesis would be extremely limited and would not justify the investment; this is also confirmed by the very low utilization of the additional scanner, reported in Figure 12.

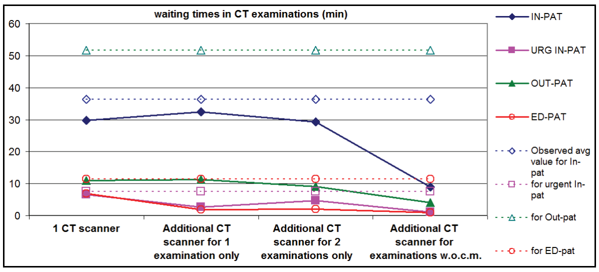

Figure 11: Limited Use Additional Scan - Waiting Times

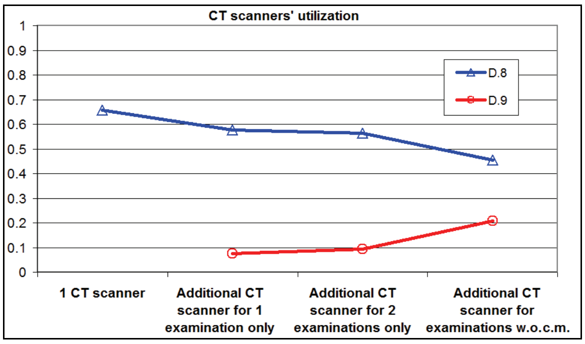

Figure 12: Limited Use Additional Scan - Scanners' Utilization

Instead, in the second hypothesis (last label in the figures) the average waiting time for in-patients would be reduced by about one third. In this latter case, being the utilization of the two CT scanners still low, an increment of out-patient throughput could be taken into consideration. This, in turn, would result in the reduction of out-patient booking queue period (assuming that the other flows of patients remain identical, because essentially linked to the served area population).

From the results showed in Figures 13 and 14 (reporting in abscissa the multiplier value for CT out-patient throughput with respect to the current value), it's noticed that it is possible to support more than twice the current throughput, maintaining the same current performance in terms of waiting time.

At last, a third hypothesis consists of introducing a second CT scanner, also identically managed. The investment and operational costs of this machine would be clearly higher and would also require additional space and human resources, such as a nurse for out-patient preparation (for contrast medium examinations).

Therefore, the investment would be justified only permitting a net increase of out-patient throughput.

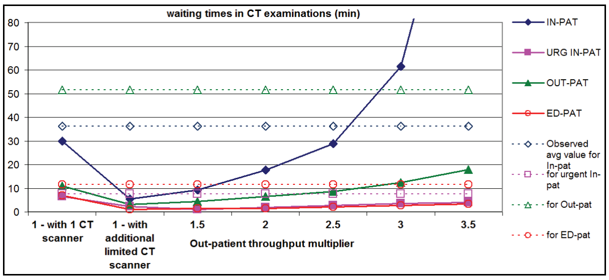

Figure 13: Limited Use Additional Scan - Waiting Times/Out-patient Flow Increment

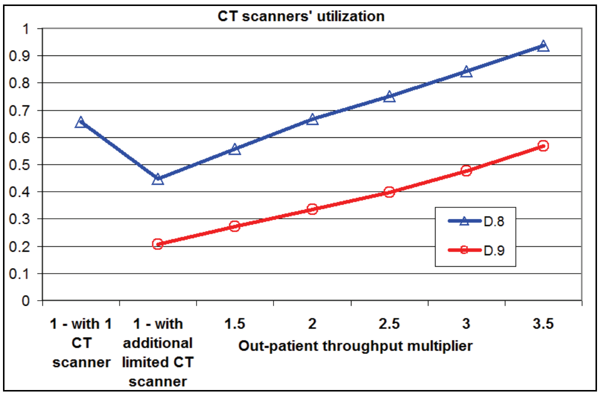

Figure 14: Limited Use Additional Scan - Scanners' Utilization/Out-patient Flow Increment

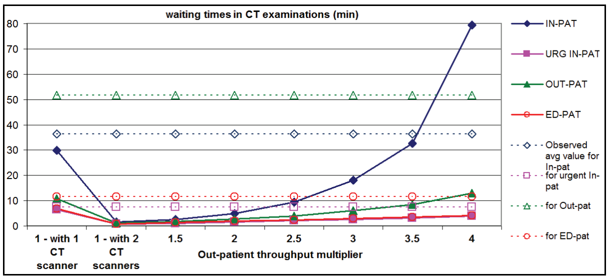

Figure 15: Additional Scan - Waiting Times/Out-patient Flow Increment

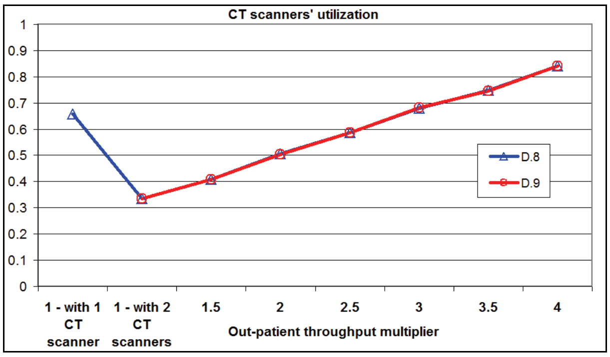

Figure 16: Additional Scan - Scanners' Utilization/Out-patient Flow Increment

The reported results in Figures 15 and 16 show that also with a factor 3.5, waiting-times for all types of patients would be similar to those with the current equipment. The utilization values of the two scanners would be, of course, identical (showing approximately a linear increase) and, with a factor 3.5, the resulting value around 0.75 would be satisfactory.

10. CONCLUSIONS

In this paper a DES model of a DRD in a hospital with different flows of patients has been illustrated. The first described step is a methodical approach, which could be adapted and implemented in similar cases, for collecting and elaborating process time data of X-ray and CT examinations. The joint use of observations and official data is justified by the huge number of different types of examinations performed on different X-ray machines, which makes infeasible, unless with a significant time consumption effort, collecting data for each of them. By means of this method, every X-ray machine has been characterized by two parameters. The first parameter is the ratio of the average process duration in a homogeneous examination reference group with respect to the document reference value (i.e. representing if the machine is slower or faster than average). The second parameter expresses the machine process variability through the shape parameter α, to be used in gamma PDFs, with variable means. For CT examinations, several maximum likelihood parameters of gamma PDFs have been derived for examinations with available observations, whereas a combined data approach has been used for examinations without sufficient observed data.

The model, realized by means of chi, takes into account the effect of priority rules assigned to the different flows of patients, which are very common in a hospital DRD and the preferential use of some X-ray machines. The central role represented by technologists, who are the shared resource among the various machines, is also highlighted. The validation of the model in terms of expected waiting times has been led satisfactorily on CT examinations. In particular, for in-patients and ED patients, for whom check-in time data, drawn from the department IS, are more reliable.

As shown in the simulation results, the model, at the implemented level of detail regarding process times, permits an easy investigation of different "scenario" hypothesis. In particular, assuming available investments for an additional CT scanner, it has been shown that this expense would only be justified by increased out-patient throughput. This increment would, in turn, result in a drop down of the average booking queue time (currently 3 months) for this kind of examinations.

Despite the obtained results are strictly related to the investigated case, the model and the method for implementing process time data in a similar radiology department could be generalized.

Future developments of the work are analysing in detail the relationship among expected out-patient booking queue time for CT examinations, scheduling policies and equipment capacity, along with a cost-benefit analysis of introducing an additional CT scanner, while taking into account investment and operational costs.

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