A process algebra based simulation model of a Diagnostic Radiology Department

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Boenzi F.*, Pilolli R.*, Rooda J.E.**

* *DIASS and DIMeG, Politecnico di Bari, Bari, Italy.*
(boenzi@poliba, r.pilolli@poliba.it)

***Department of Mechanical Engineering, Eindhoven University of Technology, Eindhoven, The Netherlands.*
(J.E.Rooda@tue.nl)

Abstract: In the last years, it's possible to observe a growing interest in applying in the health care sector tools and methods, which have been successfully applied in other service and industry sectors and have helped to improve planning and efficient use of resources, while maintaining high quality of the delivered service or product. Discrete event simulation represents a powerful and proven tool, which enables the experimentation of several possible solutions at relatively low cost. This paper is focused on the modeling and analysis of a Diagnostic Radiology Department (DRD) in an important Southern Italy hospital and adopts a discrete-event simulation approach based on a process algebra dialect, called χ. Some "scenario" results are then illustrated in order to derive basic performance indicators of the system, which could be useful to hospital decision-makers and constitute a starting point for a deeper cost-benefit evaluation.

Keywords: Healthcare system, discrete event simulation, radiology department, process algebra χ

1. Introduction

Nowadays, 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) (Lopez-Valcarcel and Perez, 1994). Hence, many health care (HC) researchers and managers have turned to OM literature from the industrial and service sectors when seeking answer to the many problems faced in delivering health services (Bertrand and de Vries, 2005). Literature shows that the most widely used tool for HC decision-makers to support their efforts in achieving their objectives is discrete-event simulation (DES) (Klafehn, 1987, Fu, 1994, Jun et al., 1999). According to (Brailsford, 2007), there are three main reasons for this: firstly, HCSs are characterized by uncertainty and variability, requiring a stochastic approach; secondly, HC organizations can be hugely complex and simulation allows to model complex realities; thirdly, the key role played by human beings in HCSs requires an approach which allows interaction and communication between modeler and user or client. HC models permit end-users (such as hospital administrators or clinic managers) to evaluate the efficiency of existing HC delivery systems, to ask "what-if" questions and to design new HC delivery system operations. DES can also be used as a forecasting tool to assess the potential impact of changes on patient flows, to examine asset allocation needs (i.e. in staffing levels or in physical capacity), and/or to investigate the complex relationships among different system variables (such as the rate of patient arrivals or the rate of patient service delivery). In a hospital organization, the Diagnostic Radiology Department (DRD) is characterized by an inherent complexity because of the nature of the provided services. These services are utilized by almost every category of patient which enters the hospital system and, in particular, they have strong inter-dependencies with an Emergency Department (ED) (Johnston et al., 2009). Hence, efficient utilization of X-ray facilities is a necessary condition for the overall hospital efficiency and these systems have been widely analyzed by means of DES (Klafehn, 1987 and Guglielmino et al., 2009). In this paper, the analysis of a DRD, by means of a DES model based on a process algebra dialect, called χ (van Beek et al., 2006), is reported. χ has been used for modeling, simulation and control of manufacturing and warehousing systems; it shows great potentialities also to understand the behavior of HCSs in terms of flow times and throughput of patients. For example, in (Ivanov et al., 2010) models of different layouts of a Magnetic Resonance Imaging (MRI) department are compared to determine the best performance (flow-time and throughput of patients). This paper is organized as follows: in Section 2, the DRD equipment and the process work-flow in the system are illustrated; in Section 3, the principal utilized input data of the model and the DES model features are described; in Section 4, different possible scenarios are presented and, in Section 5, simulation results are provided. Finally, in Section 6, conclusions and suggestions for future research are given.

2. Case study: a Radiology Department

2.1 System description

The analyzed DRD consists of machines, human technical resources to operate them, physicians for reporting the results of the examinations, medical attendants to help moving and transferring patients and administrative staff in the reception. The machine equipment consists of X-ray machines, Computed Tomography (CT) scanners and Ultrasound scanners. The ultrasound examinations have been excluded from our analysis, because the involved process can be considered as "stand-alone". Except for one case, all the machines are located in separate rooms. In addition, since there aren't dressing rooms for patients or, when present, are very rarely used, for practical reasons according to the staff experience, the room occupation coincides with the machine occupation. A first set of machines (X-ray examinations) comprises: the general purpose machines "Diagnostica" from number 1 to number 4 and "Diagnostica P.S.", which is an ED patient dedicated machine; the two special purpose machines OPT (Optometry) and BDS (Bones Density Scanner) machine, for mouth/cranial and densitometry examinations, respectively, which are located in the same room and therefore are unable to work simultaneously for space and safety reasons. A second set of machines is made of two CT scanners, designated as "CT" and "CT MS64", of which the second one is a piece of equipment of the last generation, provided with higher image resolution power. For this reason, even though the majority of the examinations could be performed on both machines (if high resolution imaging is not strictly demanded), the technologists prefer to use the second machine. Hypothetically, any kind of examination could be performed on any of the general purpose X-rays machines, except for contrast medium examinations which can be performed exclusively on machine "D.1". Furthermore, the technologists show a marked preference for machine "D.4", because it is the only "Direct Radiography" (DR) machine (on which the examination process is fully digital) and resulting as the most accurate and fast one. On the contrary, on "conventional" X-ray machines, it is necessary to digitize the resulting image, prior to be able to store it electronically in the department image DB. As regard to the ED dedicated machine, it can be used for ED patients only, but its utilization is indeed marginal because it is considered by the staff inadequate for giving a quick response, both under the technical (poor image quality) and the logistical aspect (room too tight for moving and transferring patients, mostly on litters). Technologists represent in the system a shared resource to operate the machines during the examination phase, whereas physicians represent a shared resource during the reporting phase. Only for the scanner "CT MS64" there are a dedicated physician and a dedicated technologist because, in general, their job activities are strictly complementary. Our analysis and simulation model will be focused on the examination phase only, which ends with the storing of digital images in the DRD DB, for successive retrieving.

2.2 Brief work-flow description and patient flows

The diagnostic and examination process as a whole can be summarized in five principal stages: examination request generation, reception and registration, examination execution, reporting and report delivery. Based upon the different origin of the requests, the whole examination demand origins four different flows: a) in-patients (whose examination requests are generated by physicians in the hospital departments); b) urgent in-patients; c) out-patients (planned component of the demand, whose examination requests are generated by family doctors and who are scheduled on an appointment base) and d) ED patients. For out-patients c), the number of requests to work out daily in the DRD comes from a fixed weekly schedule, set out by "CUP" (Centro Unico Prenotazione - Unified Booking System), detailed for each day of the week with a fixed number of certain types of examinations to be carried out during the two work-shifts of the reception opening time (from 8 to 14 and from 14 to 20 with different technologist numbers, from Monday to Friday, plus Saturday morning). Patients of kind 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 almost equal, c) and, finally, a). As a general rule, reception staff effort tries to arrange external planned demand and emergency or urgent demand. In our analysis, the time of arrival of a patient in the system is considered as the time instant when the reception personnel decide to register his arrival in the electronic management software of the department. For patients a), the registration time is not the time of the request creation but the time when the patient arrives at the DRD, after the receptionist has ordered his transfer from the relative hospital department. For patients c), the time of arrival is represented by the patient show up on his appointment. For patients b) and d), the difference between the time of the request generation and the registering time can be considered negligible, because of their high priority. When the reception is closed, registering job is made by the technologists themselves. Once registered, the patients wait in dedicated spaces for an inter-phone call if they can go autonomously, following signposts, to the examination room (this generally happens for out-patients) or are taken there by the medical attendants or by the technologists themselves (in-patients and ED patients, who are generally on wheelchairs, wheel-beds or litters).

3. Available data and utilization in the model

The available data, obtained from the information system of the DRD, consist of a table-sheet (in the following, referenced to as DRD-data), reporting the number of all the different examinations, with names and codes, performed in the department in the last year (2010), detailed by the used diagnostic machine and by the type of patient. In the real system, a single patient is associated to a list of examinations. However, in the mentioned data, this information is lost because only the resulting sum for a particular examination on each machine, recording the origin of the associated request (the type of patient), is shown. Since it's necessary to know the inter-arrival times of the served entities in the DRD system and DRD-data are used to derive them, in the simulated model the examination request (i.e. generation) process will be realized by means of four "examination-generators" (maintaining the distinction among internal, urgent internal, ED and external requests) and not "patient-generators", in the proper significance. We will treat the examination-requests as moving entities in the system, representing the "patients", as if, in the real system, for any patient, there were one examination only to perform. Generators are modeled as completely time-random processes (homogeneous behavior in time and no tip requests) and, therefore, implementing exponential distributions. An important assumption in the model is that the simulated time will be restricted to the reception working hours. In this way, on the one hand, it is possible to simulate the system continuously in time, without the need of employing complex routines for time checking and system configuration variation (due to the staff change during the shifts and of the permitted accessibility for the types of patients). On the other hand, it is possible to analyze the system under the most demanding conditions, because subjected to the four different flows of patients. In order to derive the average inter-arrival time intervals for the different types of patients, their last year total numbers and last year calculated reception available working hours or total yearly hours (for patients who can arrive at any time) have been used, as reported in Table I. For in-patients, the available hours have been reduced, because during some time intervals it's not possible to ask for their transfer (to avoid overlapping with some routine activities, as the daily medical check or dining time).

	In-patients (G_0)	**Urgent in-patients (G_1)**	**Out-patients (G_2)**	**ED-patients (G_3)**
Total Number	14,049	412	21,708	15,881
Available reception hours or total yearly hours	2,550	8,760	3,366	8,760
Average inter-arrival time [min/pat]	10.89	1275.73	9.30	33.10
Relative percentages in the model time-span	39.87%	0.34%	46.67%	13.12%

Table 1. Data and average inter-arrival times for the different types of patients

Furthermore, each generator has to reproduce statistically the types of the requested examinations, as can be drawn from DRD-data. To this aim, by means of an automated process, data are first sorted by the types of patients and then the frequencies of the several examinations are calculated, together with the respective cumulative frequencies. Successively, the generators in the model adopt a proper function which converts a random real number extraction in the interval [0,1) into an examination code, reading the values of the cumulative frequency distribution for the specific type of patient. As regard to the duration values of the numerous and diverse types of examinations, it has not been possible to derive any information from local data sources. For this reason, the starting point for processing time quantification in our analysis is represented by a joint official document (VV. AA., 2006), edited in the name of various Italian radiology associations (both of medical doctors and technologists). The document lays down a national codification system for all the examinations and reports for each of them the mean time needed for execution and reporting, taking into account also other activities requested by the law (information, personal approval, medical justification verification). The calculated mean times are the result of findings in 15 hospital departments and take into account also the effects of utilizing non-homogeneous technological equipment. In our approach, both the national official document and some local data obtained by direct time-measurements have been used, in order to consider the specific DRD equipment technological situation. To this aim, a series of measurements on room occupancy duration times has been performed, both on X-ray machines and on one of the CT scanners. Regarding the first set of machines, since the chest examination is the most requested one, it has been chosen as a reference case. As regard to CT examinations, the older machine "CT" is at the moment not in use and it has been possible to execute measurements on the last generation machine "CT MS64" only. The collected data result very scattered among the types of examination and, so far, only a limited number of homogeneous examinations has been registered (brain and abdomen examinations, which result also very frequent from DRD-data). The joint use of national and local data has led to assume, in the model, adjusted examination mean times, obtained multiplying the values drawn from the document by a proper factor called "*k*". This factor is differentiated for each machine, but considered constant for all the examinations on that machine, once an examination reference case has been established. A synthesis of the collected data and of the assumed values for *k* is shown in Table II. For the older CT scan, from interviews to the staff and according to their past experience, it seems reasonable to assume *k* equal to 1.

Diagnostic machine	**Number of measurements (reference case examination)**	**Average time value / national document duration [min]**	**Assumed factor *k***
D. 4	20 (chest)	5' 13" / 7'	0.75
D. ≠ 4	9 (chest)	7' 17" / 7'	1.00
CT MS64	7 (brain - without contrast medium)	8' 50" / 19'	0.50
CT MS64	7 (abdomen - with and without contrast medium)	22' 46" / 37'	0.50
CT	N/A	N/A	1.00

Table 2. Average values for reference examinations and assumed corrective factor *k*

All the machine processing times are assumed to be well-fitted by gamma distributions (with examination-changing mean values), because this assumption seems to be consistent with similar probability density functions found for them in the HC sector (e.g. in MRI examinations). In order to quantify the goodness-of-fit, a chi-square test has been carried out on part of the collected data. For machine "D.4", the sample size of the reference case (20 measurements) is sufficient to apply the chi-square goodness-of-fit test (adopting 4 sub-intervals in the data range) and results show that the gamma distribution hypothesis is rejectable with a confidence level between 0.10 and 0.25. For this machine, the calculated value of the distribution shape parameter α equals 4.9 (assumed constant for all the examinations). For X-ray machines different from "D.4" and for the newer CT-scanner, the number of the collected data is too limited for implementing the chi square test. For these last machines, all the same, a gamma distribution has been assumed too, adopting a shape parameter α drawn from literature equal to 9 (Salzarulo et al., 2010).

As regard to the activities carried out by technologists, it's necessary to include in the model that they can be busy in a series of auxiliary activities not directly related to performing examinations (i.e. directly calling patients, helping in moving non-autonomous patients, talking with doctors, physiological pauses) and, therefore, a machine/room can be free for receiving a patient, whilst a technologist can be not ready yet. The time spent in "extra-activities" by the 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 ingress time of the next patient, under the conditions that a next patient is present (if a patient were not present, whatever a technologist is doing wouldn't have any influence). Measurements carried out in four different days (48 measurements in total), let us quantify the average time spent in "extra-activities" in 3 minutes. For the sake of simplicity and according to the behavior of the process modeling this "extra-time" (described in the next paragraph), no variability for it has been assumed. The number of technologists in the model has been considered constant during the entire simulation time span. This number comes from the average of net data of a typical monthly personnel roster (4.8 per shift), rounded to the nearest integer (5), taking into account that, on some fixed days in a week, one of the technologists in the DRD is assigned to surgical assistance or to MRI examinations (out of the scope of this work).

4. Model description

The DRD has been analyzed by means of a DES model based on χ. 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. The model includes different characteristics of the system: the priority assigned to patients and the preferential use of machines; the use of a shared resource, represented by technologists; the inability of two X-ray machines to operate simultaneously, because located in the same room; the variability of processing times; "extra-activities" carried out by technologists.

The resulting model of the department, reported in Figure 1, consists of the following inter-linked processes:

- four time exponentially-distributed examinations (or patients) generators G_i, i = 0 - 3;
- a general buffer process BP;
- nine machine processes XD_j, j = 0 - 8, implementing gamma distributions;
- a fixed delay process T, for technologists' "extra-time" modeling;
- an exit process E, recording simulation output data.

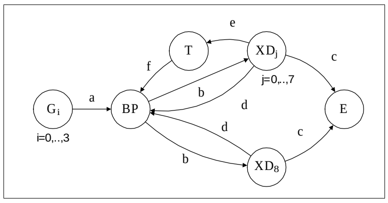

Figure 1. Model of the department

Generators send patients, through channel *a*, to a general buffer BP, in which a sorting operation, depending on the priority rules adopted for patients, is executed. The "patient" data-type contains the necessary information both for the logical execution of the simulation algorithm and for later simulation-output processing. The first set of data is made of: a priority integer number for patient sorting; a string, containing the examination code and a set of natural numbers, representing the numbered machines able to perform the particular examination code. The link between each examination code and the set of capable machines for that code is defined in a table, built aside and prior to the simulation runs from DRD-data, by means of an automated process. The second set of data consists of the entry times in the buffer (BP) and in the room/machine processes and the exit time from the system, together with the origin of the patient and the utilized machine. From the sorted buffer BP, the patients are sent, through nine channels *b*, to one of the machines (processes XD_j, j = 0 - 8), able to perform the requested examination, under the conditions that the machine isn't busy and one of the technologists is available (this condition is skipped for XD_8). If this is not possible, the patient has to wait in the buffer. In order to take into account the preferential use of machines, the list of ready machines is sorted according to a predefined integer number ranking. Technologists are modeled as a resource, shared among the different machines, except for machine "CT MS64", for which there is a dedicated technologist. At the end of every examination on any of the processes representing the machines, the patients are sent, through channel *c*, to the exit process E and a data-type containing the number of the not-busy machine and its associated preferential-use ranking number is sent, through channel *d*, to the general buffer BP, in order to be put in line in the available machines list and sorted according to the preferential use. At the same time, for all the processes, except for XD_8 (machine with a dedicated technologist), a signal, representing the leaving technologist, is sent, through channel *e*, to process T. This process is necessary to model that, at the end of the examination, the

technologist can be busy in one of the above defined "extra-activities" and not ready yet for another examination. Process T, after a fixed amount of time, releases each technologist, through channel *f*, to the general buffer BP, which collects and dispatches them back to the machines, upon request, under the constraint of maintaining constant their total number.
In the following, six different configurations of the model (which will be called "scenarios") have been compared, in order to highlight the effect of different "policies of use" of the machines and also of different machine equipment.

5. Scenario analysis

The first scenario (A) represents the situation of the system "as-it-was" according to last year data (2010), with a marginal utilization of both the ED-dedicated X-ray machine (XD_4 in the models) and of the older CT-scanner (XD_7). From the hospital data, it's possible to derive that the first was utilized for about 2.6% of the total number of ED examinations and the second machine for about 5.3% of the sole CT examinations total number. These percentages have been adopted in the model as a chance of the possible utilization of these machines for each patient, by means of a uniform distribution random extraction in the interval [0,1). If the result of the chance is negative, the machine is simply deleted from the set of examination-able machines for that patient. Since this chance represents a kind of filter for the utilization of these machines, their preferential ranking number has been assumed respectively equal to the value assigned to the direct digital X-ray machine and to the value of the newer CT-scanner. In the second scenario (B), the current situation has been modeled, because in the real system, "as-it-is" at the moment, the older CT-scanner is not in use (for maintenance problems and spare parts unavailability). Therefore, its use chance percentage in the model has been set to zero. The difference between scenario A and B is represented by the available equipment, which can be considered the consequence of a management choice if the older CT-scanner were used no longer, due to high maintenance cost. In the subsequent scenarios, however, it has been assumed that the system will continue to operate in conditions similar to those of the last year. In scenario C_1, it has been assumed a capital investment, for substituting the older ED-dedicated machine and for widening the space at disposal in the relative room, be available. Then, it would be possible to buy another direct digital X-ray machine (identical to "D.4"). Under this hypothesis, in the model, the limitation posed by the chance of its use has been discarded and on the contrary a preference value greater then that of "D.4" has been adopted. Scenario C_2, C_3 and C_4 are characterized by the same equipment, but with different policy of use of the ED-dedicated machine: in case C_2 the use has been extended to in-patients, in C_3 to out-patients and in C_4 to any patient, without distinction. Therefore, the system, in the last configuration, comprises two identical machines (also for the preference of use) which can work in parallel and there is no longer a dedicated ED-machine.

6. Simulation results and considerations

The throughput results are equal, for all the scenarios, to the reciprocal values of the inter-arrival mean times of the patients, showing that all the systems are in steady-state conditions.
As regard to the utilization of the machines, in Figure 2 (X-ray) and Figure 3 (CT), it's possible to observe a very high value (above 0.8) for machine 8 (newer CT-scanner), which is, of course, even greater in scenario B. The overall system utilization (average value among all the machines) is quite low, because of the very low demand of some particular examinations (e.g. on machines 5 and 6). Also the utilization of technologists (calculated as the weighted average of the utilization of "moving" technologists and of the CT dedicated one) appears to be low for all the scenarios; in particular, their engagement in extra-activities (calculated as the ratio of their average number in process T and the average number outside process BP) is around 30%. This means that quite one third of their working time is spent in activities different from performing examinations.
In scenario C_1, the effect of the introduction of a newer ED-dedicated machine (machine 4) results in a slight reduction of the utilization of machine 3 (from 0.45 to 0.41) and of machines 0, 1 and 2. Its utilization (0.13) would be anyway too low and not acceptable against the spent investment. In scenario C_2, and in the subsequent ones, the utilization of the two machines (3 and 4) tends to equalize, around the value of 0.32, while the utilization of machines 0, 1 and 2 is further reduced.

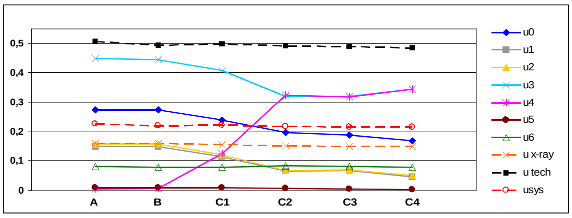

Figure 2. X-ray machines, technologist and system utilization

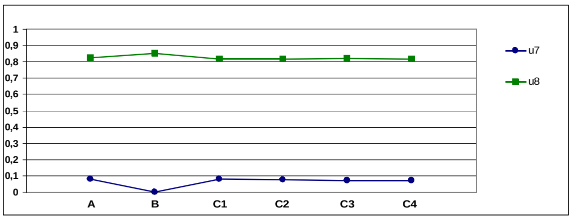

Figure 3. CT-scanners utilization

Figure 4 and Figure 5 show, respectively, average flow times and waiting times for the different types of patients in each scenario. Because of the variability of the results, the reported values have been chosen in a set of five replications, as those characterized by the greatest average waiting time value for type-0 patients (in-patients). For other types of patients, average waiting times are always in an acceptable range (under 5 minutes) and, for this reason, major attention has been addressed to in-patients. The results are in accordance with the expected behavior of the model because of the priority sorting. It's possible to notice a marked difference for in-patient average waiting time between scenario A and B (an increment of almost 35%), which means that the use of the older CT-scanner, even if marginal, represents an important help. For in-patients, the advantage of introducing a newer machine has really little influence: considering the mid values obtained from the replications and assuming scenario A as the reference case, in scenario C_1 there is an increment of around 1%, in scenario C_2, a decrement of 3.3%, in scenario C_3, a decrement of 8.7% and, in scenario C_4, a decrement of 7.7%. The results show that, as regard to the organizational choice "policy of use" of the ED-machine, the extension to out-patients (in addition to ED patients) would be more advantageous for reducing in-patient waiting time than extending its use directly to them, because of the priority issue.

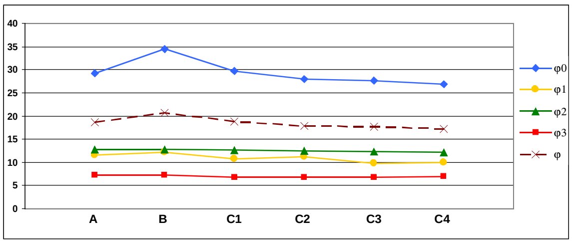

Figure 4. Average flow times [min]

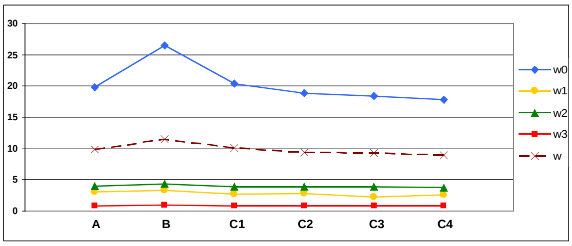

Figure 5. Average waiting times [min]

7. Conclusions and future research

In this work, a Diagnostic Radiology Department (DRD) has been modeled including the relevant aspects of the procedural work-flow emerged during several on site surveys, qualitatively from observations and staff interviews and quantitatively from direct examination-time measurements. The followed DES modeling approach and its implementation with the process algebra dialect language χ are flexible enough to permit easy adaptations to similar systems, including other DRDs. The simulation results of the built model in terms of utilization of machines and patient performance (flow-time and waiting-time) can be utilized to compare different "scenarios"; an example has been illustrated, to highlight the effect of different organizational choices in the use of machines and of a possible capital investment for a new equipment. The usefulness of modeling the system can obviously be of great importance to hospital decision-makers, who could easily understand the department work-flow and basic performance indicators, despite not needing a deep machinery technological knowledge, for the analysis and interpretation of "what-if" hypotheses.

The proposed case represents just an example and a starting point for possible future accurate assessment and cost-benefit evaluations, taking into account all the involved costs (investment and operational) and revenues. Work is in progress for the acquirement of more real (aggregated) data from the system, by using concepts as effective process time (Jacobs et al., 2003).

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