AVAILABILITY ASSESSMENT SIMULATIONS FOR ALLOCATING HUMAN RESOURCES IN AIRSPACE CONTROL CENTERS

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ABSTRACT

Airspace control systems introduced automation into functions previously performed by human operators. This situation increased the dependence on the availability of computer systems, in which degraded operation events can reduce the service level at any controlled airspace. This paper presents a relationship between availability and allocation of human resources in these centers, where maintenance and operations personnel are occasionally asked to repair losses caused by automated functions. A simulation model for the Arena tool is presented, to access availability, and then the operational point of view is explored, focusing on the required availability scenarios. The results presented herein can help determine the size of operations and maintenance teams, considering the reliability and maintainability parameters of airspace control systems.

Keywords: Availability Assessment, Human Factors, Maintainability, Simulation.

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1. INTRODUCTION

1.1 Critical Systems in Airspace Control Centers

Due to the worldwide growth in airspace utilization, airspace control systems have been increasing their technical complexity (Müller and Santana, 2008), introducing new features into the existing automation or creating additional automation of functions previously performed by human operators. Therefore, the dependence (FAA, 2006) on the availability of the computer systems used by these control centers has increased. Operational procedures and design features are established to maintain the safety integrity level of the services during degraded operation, but availability remains a critical parameter to the efficiency of these centers.

In this context, this paper presents results from a simulation model, previously developed with the Arena tool (Kelton et al, 2007), in order to show its practical application for determining the size of operations and maintenance teams needed in an airspace control center, as a function of the service level – or the availability requirements - established for that specific installation of interest, considering its reliability and maintainability parameters.

First, a summary of an availability analysis is presented. More details about this model were described in a previous paper (Pizzo and Cugnasca, 2009) in which the initial focus was devoted to the availability assessment based on comparisons among distinct architectural approaches (reliability design and redundancy policies) to achieve certain levels of required availability. The new simulations presented herein consider large size scenarios for airspace control centers (with about 30 operational positions) and focus on the results of the capability of performing adequate human resources allocation compatible with the required availability.

1.2 Concepts of Airspace Control Services

Airspace control services are performed within operational centers with structures defined by international organizations such as the International Civil Aviation Organization (ICAO, 1996). These centers are hierarchically organized with four levels of control described as follows:

a) Tower Control level (TWR), where local management of landings and take-offs are performed regarding operations of an aerodrome;

b) Terminal Area level (APP), where the air traffic control manages approach procedures for landing, as well as for take-offs for en-route flights;
c) Area Control Center level (ACC), responsible for the control functions of the aircrafts flying through the en-route airways;
d) Air Traffic Flow Management level (ATFM), responsible for statistical analysis and optimization of flow, involving long-term planning of flights.

For each level described, there is a corresponding operational time scale, in which the control of processes ranges from the decisions made in seconds or minutes, at the Tower and at the APP levels, to the control of en route operations, also involving operations of some hours, at the ACC level; while at the ATFM level tactical decision-making (Weigang et al, 2008), statistical analysis and strategy planning are performed in the scale of days to months.

1.3 Operational States of an Airspace Control Center

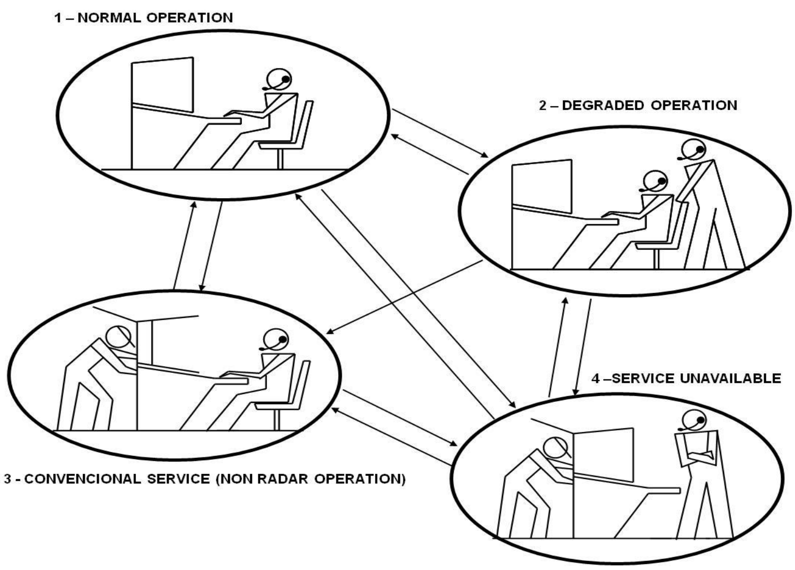
Since airspace control services are not fully automated, they intrinsically dependent from the human intervention (Pizzo and Cugnasca, 2006), a key condition to the continuity of the services is the availability of operations teams (air traffic controllers) and technicians responsible for the maintenance tasks.

In this context, the services provided within an airspace control center could be summarized in the following states, as illustrated in Figure 1:

1. Normal Service: characterized by the regular execution of services at nominal capacity, when the computer systems operate with all automation tools;
2. Degraded Mode Service: characterized by some loss in automated functions, resulting in control services being provided below their nominal capacity, therefore limiting the number of controlled aircrafts or imposing constraints on response times;
3. Conventional Service (non-radar mode): characterized by the loss of computer functions, when an operational position becomes limited just to its voice communication capabilities between controller and pilot, resulting in an all-human based control;
4. Unavailable Service: characterized by the interruption of the control services, due to either an unavailability of any critical infrastructure (i.e. controller-pilot communications, power, etc.) or critical unavailability of human resources for operation.

Transitions are previewed from the Normal state (1) to the Degraded state (2), when the system requires additional operational work from the spare operators or supervisors. A transition to the Failure state (3) occurs when a critical failure demands any service from the maintenance team. Another possible transition would take to the Unavailable Service state (4), but for the purposes of this study, restricted to the availability of the computer systems, only states (1), (2) and (3) were considered. The fourth state (4) should be considered in order to evaluate more specific issues related to other failures in the control centers infrastructure, apart from those originated by the computer systems, such as controller-pilot communication or other human factor impacts.

Figure 1: Operational States of the Services Provided in an Airspace Control Center (Pizzo and Cugnasca, 2009)



Source: Pizzo and Cugnasca, (2009)

2. AVAILABILITY MODELLING APPROACH

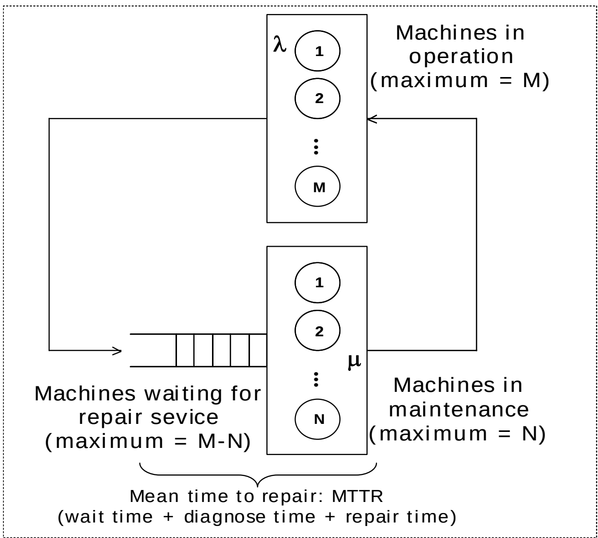
2.1 Availability Analysis Of Computer Systems With Queuing Theory Models

Summarized from more detailed descriptions available in a previous paper by the authors (Pizzo and Cugnasca, 2009), this section outlines an availability analysis model applicable to computer systems in airspace control. Using some techniques from the queuing theory, as illustrated by a data center case study (Menascé et al., 2004), the authors built a simulation model in order to study problems of staff sizing as a function of availability assessment of a data center.

One of the fundamental management problems of a computational data center is sizing the necessary maintenance staff to service the operation, in order to establish the number of machines needed to guarantee a certain confidence in the operation. That means keeping a nominal service level as expected or required by formal agreements.

In a typical computational center, the management is interested in keeping high levels of availability, by means of high reliability (reduced failure rates), as well as optimizing maintenance services, with diagnostic systems, specialized technical staff, efficient execution of repairs and quick return to operation, after any equipment that has been serviced. These parameters are related to the number of people allocated to maintenance activities, as well as to technical skills of the staff, both resulting in the meantime to repair the failed machines (MTTR). As shown in Figure 2, a closed network model can represent this operation. Some considerations are assumed for this data center: a) all machines are identical and operate independently; therefore, all of them are assumed to have the same failure rate , where λ = 1/MTTF (mean time to failure); b) each one of the M machines represents only two possible states (“operational” or “failure”); c) a diagnostic mechanism checks the operation and, when a failure occurs, the machine that failed goes to a queue to be serviced; d) in the queue, this machine waits for one of the N people of the repair staff; and e) once repaired, it immediately returns to the pool of operational machines.

Figure 2: Queuing Model for the Operational-maintenance States of a Computer Center



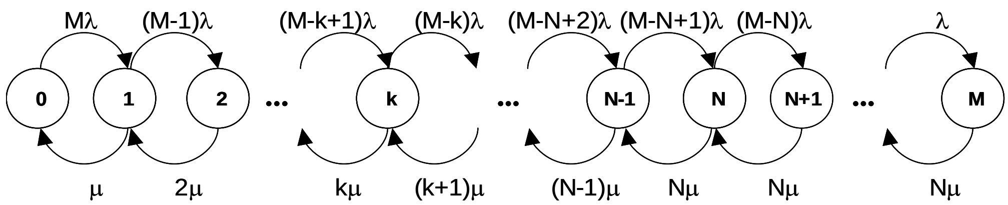
Source: Menascé et al. (2004)

The repair rate μ, equivalent to the inverse of the mean time to repair 1/MTTR, is considered to be identical for any kind of repair performed and is also independent of the technician executing the service. In case of different failure rates observed, a more complex model could be used, considering multiple class queuing models. If it were necessary to distinguish repair rates for each technician, a heterogeneous multi-server model could be defined to represent those individual rates.

As described in the cited case study, a solution for the closed queuing network can be modeled by a Markov chain (Shooman, 2002), in which each state corresponds to the situation in which there are k failed machines out of the total of M machines, with a maximum of N machines under maintenance, as illustrated in Figure 3.

The transition from state k to state k+1 occurs when a machine fails, an event that occurs with a fail rate λ multiplied by the number M-k of machines in operation. Similarly, a transition from state k to state k-1 takes place whenever a machine is repaired, a process that occurs at a repair rate μ times the number of machines being repaired k, limited to a maximum of N.μ, as the maximum number of machines under maintenance is limited to N (maximum size of the maintenance technical staff).

Figure 3: Markov Chain Model for a Data Center with M Machines

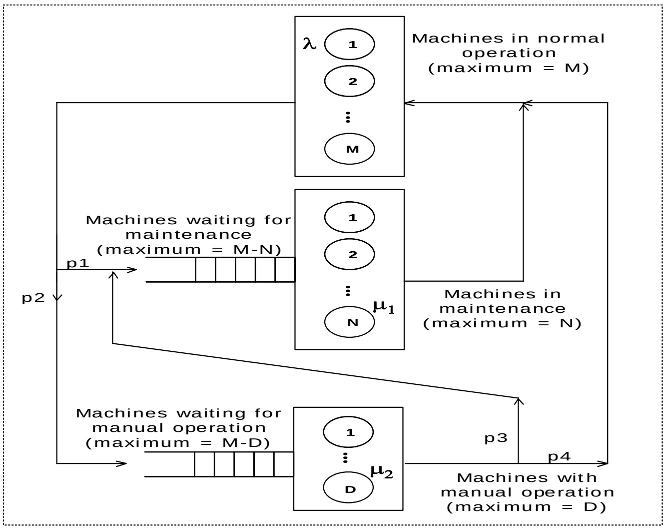


Source: Menascé et al. (2004)

2.2 Availability Model for Airspace Control Systems

Focusing on the scope application of the model previously described, a third state was considered to represent the degraded operation events existing in a real world airspace control system. Therefore, this queuing net model can be extended to the configuration illustrated in Figure 4. This new model considers not only the effect of size N of the maintenance staff, but also the effect of size D, regarding the team of extra operators available, who must be prepared to perform any manual operations necessary, being responsible for dealing with any degradation situation, when some of the automatic processes happen to be temporarily unavailable.

Figure 4: Availability Model of an Air Traffic Control Center Considering Degraded Operation



Source: Pizzo and Cugnasca, 2006

In this model, rate λ is the flow of machines that leave normal operation, corresponding to the addition of flows $\lambda.p_1$ and $\lambda.p_2$, referring transitions from normal state to failure situation (with probability p_1), or from normal state to degraded situation (with probability p_2). The return from the maintenance state to normal operation occurs with repair rate μ_1, while μ_2 represents the rate of machines that leave degraded operation, going from manual state to the maintenance condition or to the normal condition, respectively, with probabilities p_3 and p_4, thus composing flows $\mu_2.p_3$ and $\mu_2.p_4$.

3. IMPLEMENTATION OF THE SIMULATION MODEL WITH ARENA

3.1 Simulation Environment

From the queuing model previously described, this section illustrates how to apply a simulation tool in order to define an adequate number of human resources compatible with the availability of the system.

It is worth stressing that the studies presented herein aim to demonstrate practical uses and benefits obtained with the simulation model, and do not evaluate any specific real center. The main purpose of the following examples is to show possibilities and advantages of the simulation tool to determine the size of an effective team, both for spare controllers and for maintenance teams.

3.2 Inputs Considered in the Simulation Model

This item describes the input variables used in the simulation model, as follows:

- Dimension of the control system, in terms of the number (P) of operational positions;
- Reliability of the system, represented by the failure rate λ of each operational position;
- Maximum capacity of simultaneous operational service, represented by the size (D) of the available operational personnel, composed of the extra controllers or operational supervisors responsible for dealing with any event of degraded service;
- Maximum capacity of simultaneous technical service, represented by size (T) of the maintenance team, composed of engineers or technicians responsible for the repair services in case of any critical failures in the computer system;
- Repair rates corresponding to the average times spent by technical and operational teams during their service activities: rates μ_1 and μ_2, respectively;
- p_1 is the percentage of critical failures, in the total number of occurrences λ, which need services from the technical maintenance team. Derived from p_1, percentage p_2 is the share of non-critical failure events solved by operational service: $p_2 = 1 - p_1$;
- p_3 is the percentage of critical failures occurred during the operational team services, when the sys-tem migrates from a degraded condition to a technical failure condition. Derived from p_3, percentage p_4 represents the success rate of the operational team: $p_4 = 1 - p_3$, which indicates the proportion of non-critical events solved by the operational team.

3.3 Outputs Considered in the Simulation Model

This item describes the output variables used in the simulation model, as follows:

- Global availability of the system, represented by the average percentage of positions available during the simulation, compared with the total installed positions (P). When the global availability is less than 1, it means that there are some unavailable positions (outside the normal state). This does not mean, however, that the services provided have been affected, once the loss might be restricted to the margin of redundant positions installed in this system;
- Nominal Availability of the system, represented by the average percentage of available operating positions compared with the minimum number (P_n) of positions required for the provision of service in its nominal capacity. This number (P_n) was admitted to be 80% the size of the system (P): $P_n = 0.8$ P, which is equivalent to a 25% redundancy level (e.g. P_n=24 and P=30 means a system with 6 spare positions). When the nominal availability is less than 1, it means that the operation is below the required capacity, and

degradation in the services provided is thus expected, if the demand reaches its nominal load;

- Average size of the operational queue, which is the average of positions that are waiting for available controllers (operational service) during a degraded operation interval;
- Average size of the maintenance queue, which is the average of positions that are waiting for available technicians (technical maintenance service) during a period of time when any failure event demands maintenance service;
- Maximum length of the operational queue, which is the average of maximum values of the number of positions waiting for available controllers, during any events of degraded operation;
- Maximum length of the maintenance queue, which represents the average of the maximum values of the number of failure positions waiting for available technicians, during any critical failure events that demand maintenance.

3.4 Typical Scenarios Considered

For establishing typical reliability, a theoretical calculation was taken for a hypothetical air traffic control operational position, considered to be configured with commercial off-the-shelf equipment, including workstations, monitors and other peripherals, as referenced by Pizzo and Cugnasca (2009). Thus, the reliability obtained (mean time to fail) for each position was MTTF= 11187 hours, considering a typical value for critical failures at each operational position. The non-critical failures, related to common operational occurrences that could demand attention from the operational staff (such as additional workload of assistant controllers or any interaction with operational supervisors), could be measured directly, but for the purposes of this study (devoted to demonstrating the application of the simulation model), it was assumed to be a fraction of the critical failures, and was therefore defined with p_1= 1% and p_2= 99%, leading to a typical value for the reliability of each position (MTTF = 112h). If any different value was measured from an existing air traffic control center, it could also be defined as the proper relationship between p_1 and p_2, as observed.

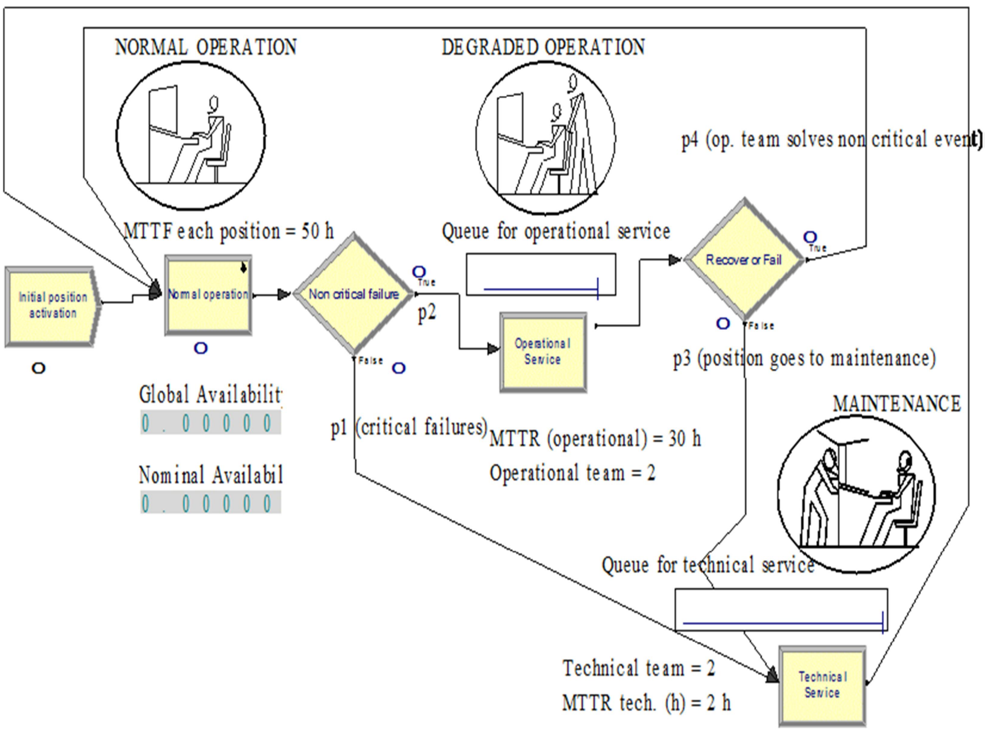
Various scenarios were simulated, representing different classes of reliability and reparability of the systems. Both high (A) and low (B) reliability classes were considered, respectively, with 200h and 50h MTTF. The same variations in reparability were also studied, considering different classes for high and low mean times needed to finish an operational repair: $MTTR_{op}$ from 0.1h(A) to 2.0h(B); as well as mean times needed to finish a technical repair: $MTTR_{tech}$ from 0.5h(A) to 24h(B).

Extending the previous study (Pizzo and Cugnasca, 2009), new simulations were conducted for large (L) size scenarios of airspace control centers, with 30 operational positions. These scenarios also considered a 25% level of redundancy, meaning that 6 spare positions were already included. The simulation model used an exponential distribution to represent the random nature of failure rate λ for electronic equipment, while repair rates μ were modeled with a triangular distribution.

In the Arena environment (ROCKWELL, 2005), the model of queues described in section 2.2 can be implemented as shown in Figure 5, with the following components:

- “Initialization” object: a closed network model requires a startup object, which periodically activates new operational positions at the beginning of the simulation, until the number of positions in the network reaches the total size of each scenario (P);
- "Normal Operation" module: simulates failure events for the positions in state 1: normal operation. Such events could lead the system to a degraded operation state or to the maintenance state. This module is simulated with an exponential distribution of failures with rate λ = 1/MTTF;

Figure 5: Simulation Model Developed on Arena



Source: Pizzo and Cugnasca (2009)

- Decision module "critical failure": responsible for routing a failed position to states 2 or 3, depending on p_1 and p_2, as described in item 2.2;
- "Operation Service" module (state 2): characterized by a queue of operational care, with repair rate $\mu_2 = 1 / MTTR_{op}$;
- Decision module "Recover or fail": responsible for routing each position in the operational service, with rates p_3 and p_4, respectively representing the migration to the maintenance service, or a possible return to the normal state;
- Maintenance service (state 3): characterized by the queue of the technical maintenance service, with repair rate $\mu_1 = 1/ MTTR_{tech}$.

4. SIMULATION RESULTS

4.1 Results from Simulations of Controller Staff

As the recommended use of the Arena tool (Kelton et al, 2007), when the purpose is to obtain significant values, with 95% confidence for the average results, the values presented were obtained from the execution of several repetitions for each scenario simulation (parameter “REPS” presented in Tables 1 and 2). This practice avoids erroneous comparisons between scenarios, which may occur when there is no proper confidence that results variations came from inputs variations, and are not caused by statistical deviation from different runs.

Each scenario is initialized and simulated many different times, with independent random root conditions. These repetitions are also called “runs” or “replications". The statistical definition of the necessary number of replications followed the same criteria adopted by Ribeiro (2003), establishing the minimum repetition number that generates convergence in the averages of results, with standard deviations smaller than 0.0001. Thus, the results presented here were obtained from the execution of at least 50 replications for large size scenario simulations.

Table 1 presents results from large size scenario simulations in order to verify ideal allocation of extra operators needed for this control center, considering LBB availability parameters. This table shows a row for each simulated scenario, with average results obtained with the total number of runs ("REPS") each one for the simulation of a five-year operation.

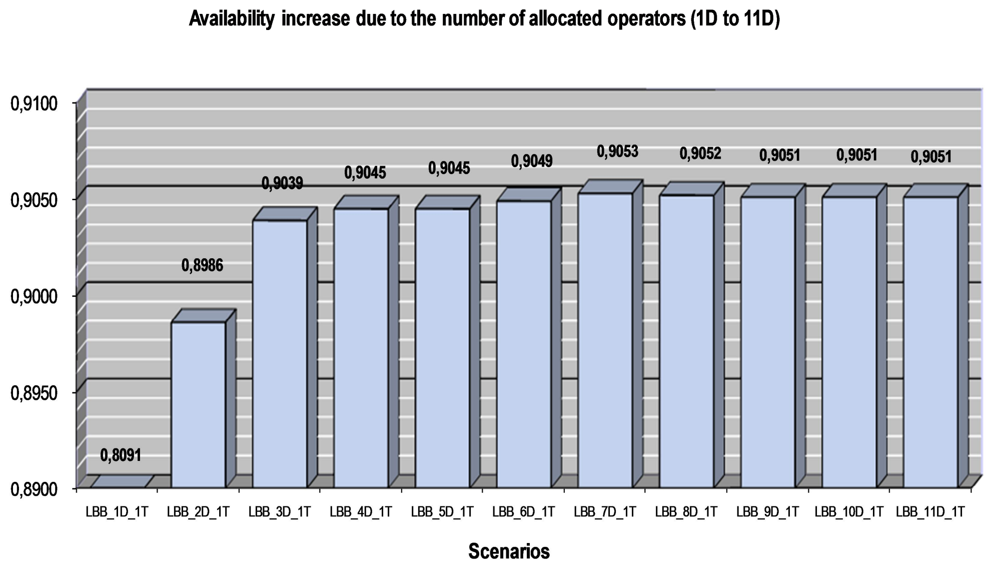
Table 1 - Results obtained from Large Scenario Simulations

Scenario Properties		Controls					Responses		
Scenario	Reps	MTTF pos (hours)	MTTR operator (minutes)	MTTR technician (minutes)	Operators (Available controllers)	Technicians	Max Op Queue (avg)	Max Tech Queue (avg)	Global availability
LBB_1D_1T	50	50	120	1440	1	1	3,752	0,742	0,8091
LBB_2D_1T	50	50	120	1440	2	1	0,218	1,158	0,8986
LBB_3D_1T	50	50	120	1440	3	1	0,033	1,155	0,9039
LBB_4D_1T	50	50	120	1440	4	1	0,005	1,165	0,9045
LBB_5D_1T	50	50	120	1440	5	1	0,001	1,169	0,9045
LBB_6D_1T	50	50	120	1440	6	1	0,000	1,159	0,9049
LBB_7D_1T	50	50	120	1440	7	1	0,000	1,149	0,9053
LBB_8D_1T	50	50	120	1440	8	1	0,000	1,155	0,9052
LBB_9D_1T	50	50	120	1440	9	1	0,000	1,156	0,9051
LBB_10D_1T	50	50	120	1440	10	1	0,000	1,158	0,9051
LBB_11D_1T	50	50	120	1440	11	1	0,000	1,158	0,9051

The inputs for the simulation are presented in a group of columns named "Controls", corresponding to the input parameters, such as: the number of extra operational personnel (spare controllers), the number of maintenance technicians and the mean times of failure and repair considered. The outputs of the model are represented in the right group of columns named "Responses", which highlights the nominal availability averages obtained, illustrating the ability of the system to operate in its rated capacity.

The results listed in Table 1 illustrate the effects of increasing the number of operational personnel over the availability of the system. Figure 6 shows that there is no improvement in the global availability with more than 6 operators, thus indicating the ideal number of spare operators allocation needed for this control center.

Figure 6: Availability Growth with the Increment in the Number of Extra Operators (Spare Airspace Controllers)



4.2 Results from Simulations of Technicians Staff

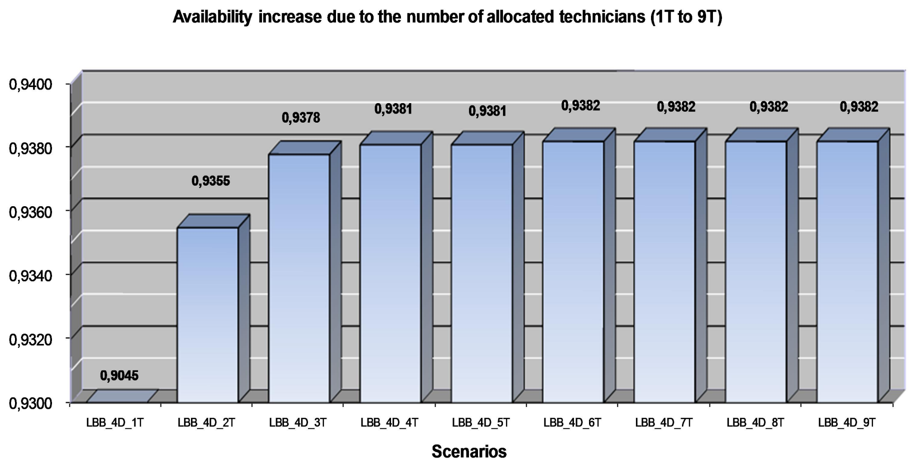
The following table presents the results of the simulation of large size scenarios, with up to 30 operational positions.

Table 2: Results Obtained from Large Scenarios Simulation

Scenario Properties	Controls						Responses		
Scenario	Reps	MTTF pos (hours)	MTTR operator (minutes)	MTTR technician (minutes)	Operators (Available controllers)	Technicians	Max Op Queue (avg)	Max Tech Queue (avg)	Global availability
LBB_4D_1T	50	50	120	1440	4	1	0.005	1.165	0.9045
LBB_4D_2T	50	50	120	1440	4	2	0.006	0.088	0.9355
LBB_4D_3T	50	50	120	1440	4	3	0.006	0.011	0.9378
LBB_4D_4T	50	50	120	1440	4	4	0.006	0.001	0.9381
LBB_4D_5T	50	50	120	1440	4	5	0.006	0.000	0.9381
LBB_4D_6T	50	50	120	1440	4	6	0.006	0.000	0.9382
LBB_4D_7T	50	50	120	1440	4	7	0.006	0.000	0.9382
LBB_4D_8T	50	50	120	1440	4	8	0.006	0.000	0.9382
LBB_4D_9T	50	50	120	1440	4	9	0.006	0.000	0.9382

The scenarios of rows 2 to 10 in Table 2 indicate improvement in the system availability by the allocation of more technicians in the maintenance staff. In these cases, Figure 7 shows that there is no significant improvement in the global availability of the system from the allocation of more than 3 technicians. This happens due to the same reason found in the previous scenarios, when the queues stop forming due to the permanent existence of at least one technician available whenever a machine needs maintenance service.

Figure 7: Availability Increase Due to the Increment in Number of Allocated Maintenance Technicians in Large Size Scenarios



5. CONCLUDING REMARKS

An extension of a previous study was presented demonstrating the application of a simulation model for assessing the availability of computer systems used in airspace control centers. The previous paper focused on the results of the simulation tool to generate contributions to the design of the computer systems in these centers, by means of comparing different technical approaches to achieving a desired level of availability, both by means of design (reliability increase) and by means of redundancy policies. This paper focused on the application of the simulation model for determining the size of proper human resources compatible with the availability of an airspace control system. The model presented can be used both as a tool for assessing the availability of critical systems as a function of its reliability and maintainability parameters, as well as being applicable to achieve an appropriate allocation of human resources, both in terms of spare operators and in terms of maintenance technicians compatible to the availability requirements, or service level agreement established for an airspace control center.

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